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Evaluation of LEEDä Using Life Cycle Assessment Methods

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Definitions of Terms

Throughout this report after initially naming a commonly used term an acronym will be substituted. A table is provided here for reference.

General Terms **Abbreviation**	**Name**
BEPAC	Building Environmental Performance Assessment Criteria
BREEAM	British Research Establishment Environmental Assessment Method
CHP	Combined Heat and Power
EA	Energy and Atmosphere, one of the impact areas of LEED
EPA	Environmental Performance Assessment
GBA	Green Building Assessment Method
ID	Innovation in Design Process, one of the impact ares of LEED
IEQ	Indoor Environmental Quality, one of the impact ares of LEED
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LEED	Leadership in Energy and Environmental Design
MR	Materials and Resources, one of the impact ares of LEED
SS	Sustainable Sites, one of the impact ares of LEED
SWH	Sam Wyly Hall
TAG	Technical Advisory Group
UM	University of Michigan
USGBC	U.S. Green Building Council
WE	Water Efficiency, one of the impact ares of LEED

Credit Specific Terms

Abbreviation	Name	Credit
CDW	Construction and Demolition Waste	MR2
CRR	Construction and Demolition Waste Recycling Rate	MR2
MR2	Construction Waste Management, a Materials and Resources credit	MR2
MSW	Municipal Solid Waste	MR2
MR4	Recycled Content, a Materials and Resources credit	MR4
PC	Post-Consumer	MR4
PI	Post-Industrial	MR4
RCR	Recycled Content Rate	MR4
RCV	Recycled Content Value	MR4
EC	Extraction Cost	MR5
ER	Extraction Rate	MR5
HMLC	High Mass Low Cost	MR5
LMHC	Low Mass High Cost	MR5
MC	Manufacturing Cost	MR5
MFR	Manufacturing Rate	MR5
MR5	Local/Regional Materials, a Materials and Resources credit	MR5
ASH MC	ASHRAE Minimum Compliance thermal model	EA1
ASHRAE	American Society of Heating, Refridegeration and Air-conditioning Engineers	EA1
DEC	Design Energy Cost	EA1
EA1	Optimize Energy Performance, an Energy and Atmosphere credit	EA1
ECB	Energy Cost Budget	EA1
ESP	Energy Savings Percentage	EA1
REC	Renewable Energy Contribution	EA1
SWH BC	Sam Wyly Hall Base Case thermal model	EA1
BIPV	Building Integrated Photovoltaics	EA2
EA2	Renewable Energy, an Energy and Atmosphere credit	EA2
LR	Lifetime Replacement	EA2
REP	Renewable Energy Percentage	EA2
SI	Single Installation	EA2
CRS	Center for Resource Solutions	EA6
EA6	Green Power, an Energy and Atmosphere credit	EA6
ECAR	East Central Area Reliability Coordination Agreement	EA6
FER	Fossil Energy Ratio	EA6
NERC	North American Electric Reliability Council	EA6

INTRODUCTION

Need for Environmental Assessment of Buildings

Nationally and globally, commercial buildings contribute significantly to energy consumption, as well as to other environmental impacts, such as air emissions and solid waste generation. For example, 38% of US primary energy consumption is related to building operations [1] [Table 2.1a], and 65% of all 1997 Municipal Solid Waste [2], [3]. Buildings are an exceedingly complex industrial product with a lifetime of decades. Emerging health issues related to the environmental impacts from buildings, such as the so-called “sick building” syndrome, have intensified awareness of the role buildings play on our environmental well-being. While certain efforts have been on-going to control and manage individual aspects of the environmental qualities of buildings (i.e. energy codes, automation and control schemes, thermal comfort), comprehensive approaches have been lacking, [4], [5] particularly in the design stages of a building’s life span. Unfortunately it is in the design stage when the greatest opportunities are available to affect changes whose benefits can last for decades. In the last decade new methods have emerged that regard buildings as a network of interrelated environmental impacts and seek to juggle these impacts to create a more integrated and environmentally benign building [6], [7].

Environmental Assessment: Two Approaches

Significant research efforts have already focused on specific aspects of buildings such as material properties, equipment performance and simulation of building physics. Much research has also explored building-related environmental performance in areas such as energy consumption, daylighting, recycled materials and air quality. However as owners, designers, regulators and occupants increasingly desire that the entire building provide improved environmental performance, integration of these individual research strands is required.

Generally, integrated approaches to understanding environmental impacts falls under the description of environmental assessment. Assessment has the dual goals of documenting environmental impacts and communicating those impacts to an intended audience. Any given party may conduct an environmental assessment for internal purposes, such as examining processes, or it may be part of a larger effort to communicate environmental information to consumers, regulators or investors. Currently, there are several methods that attempt to assess environmental impacts related to buildings. Each system has its own set of assumptions and limitations, each is designed to address certain aspects of environmental impacts and further, each system is designed for utilization by different participants in the building process, a condition that can “profoundly influence the outcome.” [8].

There are two primary methods of communicating environmental attributes that relate to buildings, which will be discussed here, Eco-labeling and Life Cycle Assessment (LCA). While many eco-labels are derived from LCA procedures, they are differentiated here on the basis of their reporting formats.

Eco-labeling: Marketing and Policy Tool

Eco-labeling is the practice of branding environmental qualities of a product or system so that consumers can more easily make environmentally based decisions.

> In simple terms, environmental labeling is defined as making relevant environmental information available to the appropriate consumers. Environmental labeling is the practice of labeling products based on a wide range of environmental considerations (e.g., hazard warnings, certified marketing claims, and information disclosure labels). Labeling contributes to the decision-making process inherent in product selection, purchasing, use and disposal, or retirement. Yet unlike most regulations that affect the behavior or actions of a limited number of entities (e.g., facilities or companies), labeling is designed to influence all consumers. In this context, the definition of "consumers" encompasses all individuals and organizations making purchase decisions regarding products and services, ranging from procurement officers of governments and corporations to individual retail consumers. Environmental labeling often also affects manufacturers and marketers as they design and formulate products that must compete based on quality, price, availability and, to varying degrees, environmental attributes. [9]

Eco-labels are appealing to manufacturers as a marketing tool because they can convey environmental qualities without revealing proprietary information. They are often appealing to environmental advocates as a policy tool, based on the assumption that informed consumers will stimulate market demand for environmental products, driving manufacturers to compete for environmental performance [9]. When eco-labels first began to appear on products claims were often inaccurate or misleading ("recyclable", "eco-friendly") and as a result consumer confidence suffered. Many governments or third party organizations responded by assuming responsibility for eco-label certification processes in order to ensure validity of labels [10]. Each label has a different set of criteria, which underlie its results. In some cases it may be a single attribute such as "75% recycled", in others it may be the result of a more comprehensive process analysis such as "certified sustainable timber" or utilize a life cycle assessment approach.

However, eco-labels themselves include limited or no information describing the basis for the certification so consumers cannot evaluate the value of the label itself. In situations where there is a respected and robust certifying process (the California Organic food standards for example) this may be less problematic, but criticism has been raised about industry dominance of certifying organizations and low thresholds for standards [10] a situation than can lead to eco-labels with low actual environmental value. Questions are also raised about possible conflicts between ecolabeling schemes and free trade agreements because of competitive exclusion issues [11].

Eco-labels in the building industry do exist, although to date the majority cover building materials or equipment rather than whole buildings [5]. Examples include Energy Star for appliances, the Forest Stewardship Council's certified wood, and Scientific Certification Systems' recycled content certification. Existing whole building labels include EnergyStar for Buildings and the British Research Establishment's Ecopoints. While it may be desirable from an implementation perspective to create an eco-label for whole buildings there are complications because, "The product of the construction industry is too complex to satisfactorily give eco-labels to buildings" [12]. Comparability is critical for an eco-label to have validity. Buildings are each unique products, and thus a whole building label, which tries to condense evaluations to a single result, is likely to be too simplified in its criteria to be of much value. "Not only are fewer attributes analyzed, but a product receiving a label for a single attribute may in fact have an overall negative environmental impact due to its other attributes" [9].

However the power of an eco-label to create market change cannot be ignored [13], [14], [9]. Both consumers and industry would like to see a building assessment tool that is sufficiently robust to be valid and one that can facilitate decision-making at key stages in the process. But in order to be useful, results of an assessment must be simple to understand and easily communicated [12], [15]. While the more comprehensive assessment schemes accomplish the first two goals, eco-labels perhaps can best address the third point.

Life Cycle Assessment (LCA): Scientific Foundation

LCA is a comprehensive methodology [16], [17], [18] whereby all the material and energy flows of a system are quantified and evaluated. Typically, upstream (extraction, production, transportation and construction), use, and downstream (deconstruction and disposal) flows of a product or service system are inventoried. Subsequently, global and regional impacts are calculated based on energy consumption, waste generation and a select series of other impact categories (i.e., global warming, ozone depletion, & acidification). This is often referred to as a "cradle-to-grave" approach. LCA allows the impacts from discrete systems and materials to be weighed against each other.

The structure of an LCA is a key element to its value. By documenting the specific procedures, data sources, boundaries and assumptions utilized, an LCA promotes clarity of information and allows for greater comparability of products. Table 1 describes the general format for an LCA, according to ISO 14040 [18] conventions.

LCA Phase	**Primary Activities**
Goal & Scope Definition	Life Cycle Definition Functional Unit Definition System Boundary Definition Data Quality Determination
Inventory Analysis	Data collection Quantification of inputs/outputs
Impact Assessment	Classification Characterization Weighting
Interpretation	Reporting Critical Review

Table 1: ISO 14040 Format

LCA in the construction industry is less developed today than in other industries, but is evolving into an essential element of building assessment [19]. "The notion of life cycle assessment has been generally accepted within the environmental research community as the only legitimate basis on which to compare alternative materials, components and services, and is therefore a logical basis on which to formulate building environmental assessment methods [8]." Several researchers have applied LCA methods to specific aspects of buildings [20], [21], [22], [23]. Recent studies have tried to use LCA to document the impacts of a whole building, considering all building materials and operation [22], [24], [25]. Several recent computer programs incorporate LCA methods into tools for design and analysis of buildings such as BEES [26], Athena [27] and Envest [28]. However, because of data limitations, the large range of construction techniques, material and system choices in buildings, none of these tools are currently capable of modeling an entire building, or computing environmental impacts for all phases or processes. Some programs have an abundance of material information but no integration with operational activities, other programs only contain data for generic building components.

Criticisms of the LCA methodology focus on conflicts between depth and applicability [5], [14]. For example a comprehensive LCA may not be easily interpreted, but if results are overly aggregated, underlying but significant details may be obscured. Additionally, transparency of processes is important for the validity of an LCA, however this may dissuade many from participating because of concern over proprietary information. Finally, there is an imbalance in current assessment criteria [8]. Certain criteria (such as energy consumption, global warming potential) are more easily measured and their methods are well established, while others (such as ecotoxicity, resource depletion) are complex to assess and their methods are strongly contested. While both kinds of criteria are desirable in an LCA, it is only the ones that are accessible which frequently are included.

The complexities of buildings require the specificity and rigor of an LCA approach to provide meaningful assessment, but difficulties in conducting an LCA as well as difficulties in interpreting and communicating the results prevent them from being utilized more generally.

LEED: A Middle Path?

A new program has emerged in the U.S., which attempts to wed elements of the previous two assessment approaches into a national "Green Building"[1] rating system. The Leadership in Energy and Environmental Design (LEED) rating system is not the first green building program in the U.S. but it is the only program with national scope and the only program that has been adopted by many private organizations (Herman Miller, Ford Motor Co., Natural Resources Defense Council) as well as local (Portland OR, Seattle WA, San Jose CA) and federal (GSA, Department of State) government bodies.

History of LEED

The U.S. Green Building Council (USGBC) is a nonprofit organization that was formed in 1993. The USGBC is made up of building industry stakeholders such as architects, building product manufacturers, owners, contractors and environmental groups who are interested in the promotion of green building in the U.S. The USGBC is a committee-based, voluntary, nongovernmental organization. Early council members advocated the development of a system to define green buildings. After researching existing programs (especially the British BREEAM and Canadian BEPAC) and metrics the council decided to develop a custom system for U.S. buildings. In 1998 the LEED 1.0 pilot program was released. By March 2000, 12 buildings had been certified under the pilot program. During the pilot period extensive revisions were underway and by March 2000 LEED 2.0 was released. LEED is developed by a steering committee of the USGBC, which coordinates input from each of the different LEED programs (LEED for New Construction, LEED for Existing Buildings, LEED Commercial Interiors, LEED Residential, LEED Core and Shell, and LEED Multiple Buildings). This report only concerns LEED for New Construction, contained in the LEED 2.0 reference guide [29]. Five Technical Advisory Groups (TAGs), one for each impact area of LEED, define program features. The TAGs, made up of "expert" volunteers from the building industry, also resolve program

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[1] "Green buildings" is the common term for a building with increased environmental performance over current norms.

interpretation issues and work on revisions to the program. The LEED steering committee also "directs technical issues that require expert research and consideration" [30] to a Technical Scientific Advisory Committee.

LEED has experienced exponential growth in the U.S. since the release of LEED 1.0 in 1998. There are 1400 member organizations in the USGBC. Currently there are 465 registered projects, representing 67 million ft^2 (not including parking). Almost 1500 people consider LEED of enough value to take an exam to become a "LEED Accredited Professional". Regional Chapters have sprung up around the country to facilitate local green building activity and LEED implementation. However only 14 buildings were certified under LEED 1.0, and to date (July 2002) only 8 buildings have been certified under LEED 2.0. In the next few years hundreds of buildings will complete the certification process representing millions of dollars of investment and thousands of hours of time, all with the goal of improving the environmental performance of buildings.

LEED Program Organization

LEED is a voluntary rating program whose goal is to "evaluate environmental performance from a whole building perspective over a building's life cycle, providing a definitive standard for what constitutes a 'green building'"[29] [2]. According to the USGBC [31], LEED was created for the following reasons–

- Facilitate positive results for the environment, occupant health and financial return
- Define "green" by providing a standard for measurement
- Prevent "greenwashing" (false or exaggerated claims)
- Promote whole-building, integrated design processes

LEED is a credit-based system. 64 credit points are divided among 5 environmental impact areas –

- *Sustainable Sites (SS)*
- *Water Efficiency (WE)*
- *Energy and Atmosphere (EA)*
- *Materials and Resources (MR)*
- *Indoor Environmental Quality (IEQ)*

In addition there are 5 credit points for *Innovation and Design Process (ID)* activities. There are prerequisites in 4 of these areas that every building must meet and several credit options in each area. Many credits have several tiers for increasing performance achievements. In order to earn a LEED certification a minimum of 26 points must be achieved (in addition to all the prerequisites). (See appendix A for a complete credit list). A Silver rating is achieved by earning between 33 and 38 points, Gold between 39-51 and Platinum between 52-69.

Every credit consists of a description of intent, requirements and documentation submittals. In many cases there is a referenced standard and credit calculation procedures. Credit requirements are accompanied by descriptive information about economic, environmental and community issues related to the credit. In many cases, examples and additional resources are also listed.

The LEED process consists of registering a building project and then fulfilling the credit requirements and submitting the required documentation. Additional costs for the LEED certification process can run into the tens of thousands of dollars [32].

LEED as Environmental Assessment tool

Clearly LEED has been a success as a tool for marketing green building and as a stimulant for policy change. The USGBC is committed to being an independent third-party for validation of green buildings. From that perspective LEED stands poised to become the dominant eco-label for green buildings. But how does it fare with the other end of the assessment spectrum? How comprehensive is a LEED certification? How transparent? How well balanced are individual credits in a LEED assessment? How comparable are LEED certified buildings?

While an immense amount of effort went into the development of LEED it was by no means a scientific process. Voluntary industry stakeholder committees made up of experts and interested parties developed program features, a format which West [10] particularly warns can potentially lead to industry favor and watering down of environmental standards. While there have been many popular press articles about LEED [33], [34] describing its progress, there has been little comprehensive study of the program. Two reports have investigated economic and implementation issues, [35], [36] and one has included a limited environmental analysis in a primarily economic investigation [37].

Why is an evaluation of LEED relevant to architecture?

Architects have a central role in the development of environmental building practices. They are in the unique position of integrating many competing elements of a building into a cohesive and successful form. Many of the technical aspects of a green building also have architectural implications (Appendix B). Alternative glazings affect lighting distribution and natural ventilation creates a host of complex spatial issues that are best resolved by an architect. There are opportunities for a greatly enhanced architectural vocabulary to emerge around green buildings, a nurturing vocabulary that fundamentally recreates the role of buildings in the environment. However, in order to achieve a harmonious integration of any of these features, a comprehensive approach to feature selection must be employed. It is impossible for an architectural practice to have the technical expertise in every system or material that might be deployed in the design of an environmentally friendly building. Nor is it desirable, because it would distract from the critical integrating function of an architect. Rather, environmental features need to be accessible in a consistent and coherent form, so they may be utilized within the context of all the other competing factors (aesthetics, economics, performance, safety, utility) in building design. Currently there is a host of well-developed means for architects to approach integration of other factors. In general these means take the form of standards.

Technical standards are the foundation on which every building's success relies. Without the standards developed by ASHRAE, IEEE, NFRC and their ilk it would have been impossible for architecture to evolve to the degree it has. Architects rely on standards as tools, which shape the myriad possible solutions into functioning reality. Standards are a means of codifying discrete technical knowledge bases into manageable architectural terms, which frees the architect to manipulate the results according to the needs of their discipline. For example without NFRC ratings architects would be unable to specify windows according to performance designs. The complex and competing elements of aesthetics, performance and function that architecture seeks to fuse would be sheer chaos without standards. As broad environmental impact becomes another facet of architectural concern it is to standards that architects turn once again to provide the tools to shape this concern into architectural solutions. Existing standards have addressed many elements of environmental impacts, but they are often independent of each other and have no interface, which has resulted in poorly integrated solutions of limited effectiveness. LEED is promoted as a "standard to define 'green.'"[31] and hopes to become the standard of environmental impact measurement in buildings. However it has not been developed with the scientific rigor of other important standards in architecture and as such is in danger of undermining its own goals.

It is architects who are currently the front line of LEED users. In the building delivery industry, it is architects who make up the majority of USGBC members, indicating their central role in LEED implementation. [38] (Figure 1). Because LEED is presented as a standard, architects have limited incentive to evaluate the environmental benefits of individual credit options. However if the standards do not reflect environmental impacts fairly, buildings of widely different impacts could hold similar ratings. A lack of consistent standards in buildings rating could have detrimental effects on both individual building performance and the success of broader environmental policies. Thus an evaluation of the quality of LEED as a standard is especially critical for architects, who are coming to rely on the program to facilitate their environmental design decisions.

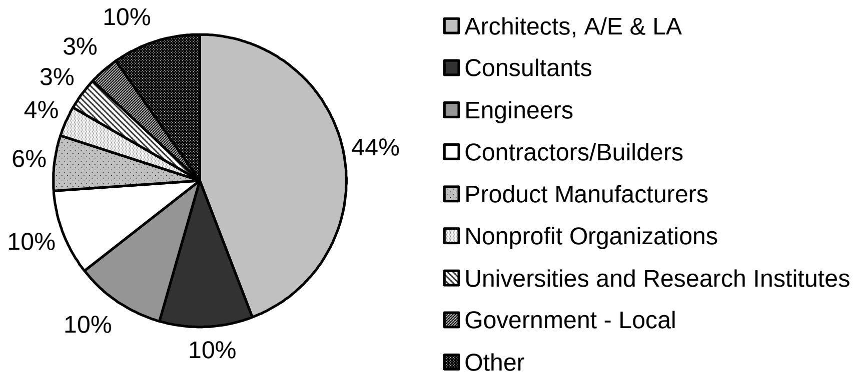

Figure 1: USGBC membership breakdown

RESEARCH OBJECTIVES

Goals and Methods

This project proposes to initiate a critical analysis of the LEED program. The goal of this project is to undertake an evaluation of individual credits within the LEED program utilizing a life cycle approach based on a case study building. Specifically this project will measure changes in life cycle energy consumption and solid waste generation in a "status quo" building resulting from the simulated implementation of LEED credit requirements. By simulating a variety of different decisions that could be made in the process of fulfilling a LEED project, a range of impacts that could be experienced within individual LEED credits will be detailed. This project hypothesizes that LEED criteria are an insufficient basis for decisions intended to optimize building environmental performance.

The simulations are based on the Sam Wyly Hall Life Cycle Inventory (SWH LCI) [39], which was conducted according to ISO 14040 LCA methods. Each of the individual credit simulations adheres to ISO conventions, however classification, characterization, weighting and critical review from the Assessment and Interpretation sections are not included.

This project will be restricted to analyzing the energy and solid waste impacts of a subset of the LEED credit options from the *Material and Resources* (MR) and *Energy and Atmosphere* (EA) sections of the program. While this approach by no means captures the whole environmental profile of a building's impacts, or the intended scope of the LEED program, it serves as a starting point for an analysis of LEED. There are many environmental impacts that are addressed by individual LEED credits and by the program as a whole that this project cannot address. Additionally, there are possible implementations of each credit that this report cannot simulate. The intention of this project is not to provide an absolute and comprehensive analysis of the entire LEED program, but rather to initiate an investigation of some of the environmental impacts related to LEED program implementation. Such an investigation will hopefully reveal possible areas of concern and suggest future avenues of improvement for the program (see appendix C for a conceptual diagram of the LEED scope and this project's scope within LEED).

Each credit is simulated by first, determining LEED requirements, secondly by researching life cycle impacts of satisfying those requirements and thirdly, by integrating the credit requirements into the SWH LCI model so that they can be characterized in terms of impact to this specific case. The credits simulated in this report are -

- MR2: Construction Waste Management
- MR4: Recycled Materials
- MR5: Local/Regional Materials
- EA1: Optimize Energy Performance
- EA2: Renewable Energy
- EA6: Green Power

Outline of Sam Wyly Hall Life Cycle Inventory

Case Study Building

SWH is a 7,306 m^2, 6-story building completed in 1997 on the University of Michigan (UM) campus in Ann Arbor, Michigan. The basement and floors 1-3 are classrooms and open-plan offices, floors 4-6 are used as hotel rooms. A 75-year life span is presumed. It is further assumed that the energy mix will be constant over the life span. Please refer to appendix D for further information on the boundaries, data sources and omissions of the SWH LCI [39].

SWH Life Cycle Phase Definition Changes

Definitions of life cycle phases in the SWH LCI have been changed for clarity and follow Scheuer [40]. Data sources remain the same as in the SWH LCI. Figure 2 is an illustration of the life cycle phase activities in the SWH LCI.

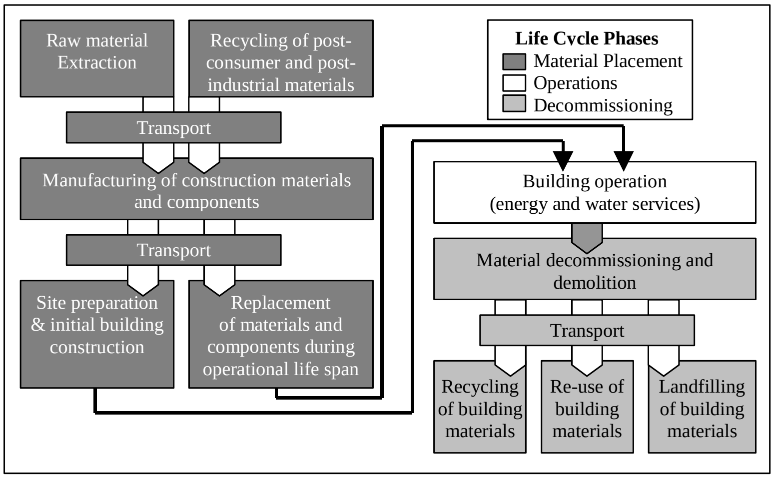

Figure 2: Life cycle phase diagram

<u>Material Placement.</u> Material placement encompasses all activities required to construct and renovate a building throughout its life span. These activities include material production, transportation and construction/renovation. The material inventory includes burdens associated with raw materials extraction and manufacturing. Replacement materials are modeled with the same energy and environmental burdens as the initial installed materials. Generally the data sets used internally account for transportation burdens from the point of extraction to the manufacturer, thus transportation covers shipping of materials from manufacturing site to construction site. Energy and environmental flows associated with the construction process could not be developed directly, therefore the Canadian Athena [27] model and work by Cole [41], [20] is used to estimate construction energy.

Operations. Operational activities consist of heating, cooling and ventilating the building, water supply and waste water treatment (based on results from a recent water services LCA[2]), water heating, lighting and equipment operation. Architectural, mechanical and internal loads and use patterns are modeled in eQuest. For SWH about 70% of the annual electricity and all of the heating and cooling steam is generated in a natural gas (NG) boiler and turbine driven combined heat and power plant (CHP). Due to difficulties in modeling the UM CHP a natural gas industrial boiler data set and a natural gas turbine data set were used to model heating/cooling and the university portion of electricity production respectively. The remaining 30% of electricity is provided by the local utility, and is modeled with an ECAR[3] grid electrical production data set.

Decommissioning. As demolition data for SWH is not available, a Canadian study of structural deconstruction [27] is used to estimate demolition energy. This study assumes material recycling based on common industry practices. Following the U.S. E.P.A. “Second Allocation Method” [16] recycling benefits SWH only by reduced waste generation, not by reduced material embodied energy.

Thermal Modeling Changes

In the SWH LCI an Energy10 [42] model was used to estimate energy consumption on an annual basis. Due to EA prerequisite 2 (ASHRAE 90.1 compliance), this report needed to model more specific changes than Energy10 is capable of. As a result an eQuest [43] thermal model was developed. In the process of developing the eQuest model a review of the assumptions about SWH systems were undertaken. The result of this process is a higher energy usage prediction. Table 2 illustrates the changes between the two models and compares them to UM’s reported 2000-01 consumption data for SWH [44]. While the change from the original SWH LCI model is significant, it appears to be more in line with the actual performance of SWH.

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[2] Forthcoming from the Center for Sustainable Systems

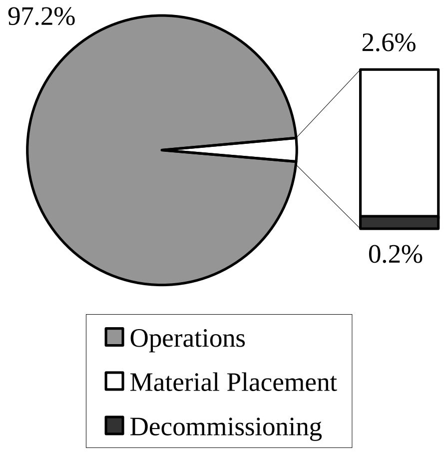
[3] East Central Area Reliability Coordination Agreement

	kBTU/m^2		
	Energy10	**eQuest**	**UM**
electric, lighting	272	231	
electric, other	160	346	
electric, total	*431*	*577*	*387*
heating	161	256	
cooling	242	628	
heating/cooling total	*403*	*884*	*1162*
Total	**835**	**1461**	**1549**

Table 2: Comparison of Energy10 and eQuest thermal model results for SWH

General findings of SWH LCI

Based on the revised thermal model the SWH status quo energy consumption and solid waste generation throughout the building's 75-year lifespan is projected at 2,300,000 GJ and 8,600 tonnes respectively. Energy and solid waste burdens are distributed across life cycle phases according to figures 3 and 4 below. These results represent the status quo base case from which all the following simulations are derived.



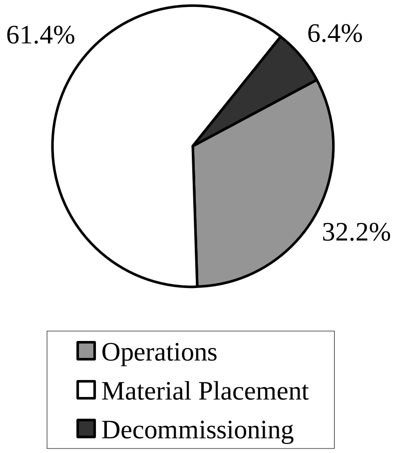


Figure 3: SWH life cycle energy consumption

Figure 4: SWH life cycle solid waste generation

Individual Credit Simulations Format

Each of the 6 credits simulated will be presented in the following order:

- Intention - The intention of the credit, including the LEED 2.0 Reference Guide description as well as some background information.
- Structure – A description of credit requirements, including any equations used in the calculation of the credit.
- Calculation Discussion - Effects of the credit calculation procedures on realization of credit intention, especially as they influence the simulation outcomes.
- Simulation: Key Parameters - Each simulated credit has different defining parameters because of environmental impacts or influence on the credit. Generally the effects of the calculation procedures are key parameters that will already have been discussed in the preceding section.
- Simulation: Methods - The methods used to simulate the given credit through the SWH LCI model, including an explanation of the modeling procedures and source material.
- Simulation: Results - Energy and solid waste impacts from the simulations in terms of the different scenarios modeled.
- Analysis - A critique of the individual credit and its current application in LEED based on the simulation results and credit calculation discussion
- Recommendations - Specific recommendations that would contribute to the individual credit better achieving its stated intention. Individual credit recommendations are specific to the credit and are irrespective of the individual credit's value against other credits. Intracredit comparisons and recommendations will follow individual credit sections. Recommendations are divided between near term and longer term, based on a subjective consideration of the difficulty in implementing the suggested changes, the amount of further research such a change might require, or the distance from industry capability such a recommendation is.

Boundaries of Simulations

This report is not going to address the documentation requirements for each credit. This is not an analysis of the practical details of the program. Further this report will not analyze the specific language of the reference manual.

LEED 2.0 requires specific prerequisites for any rated building. The prerequisites are intended to ensure that every LEED certified building meets a minimum standard for all the credit areas. While this report only simulates credits from the MR and EA sections, It is important to ensure that the SWH status quo model meets these prerequisites. The SS and IEQ prerequisites were assumed to have negligible impact on total life cycle energy use and solid waste generation. The MR prerequisite, “storage and collection of recyclables”, also has negligible impact because additional material burdens for on-site recycling facilities are insignificant and on site operations phase occupant waste generation is not included in the SWH LCI. EA prerequisite 1, “fundamental building commissioning”, is intended to ensure that systems perform as specified. Only specified operational characteristics are modeled in the SWH LCI, and there is no modeling of changes in performance over time. EA prerequisite 2, “minimum energy performance” requirea a building meet the ASHRAE 90.1, 1999 guidelines. The status quo performance of SWH exceeds an ASHRAE 90.1 version (see the EA1 credit simulation for a complete description). EA prerequisite 3, “CFC Reduction in HVAC equipment”, was not modeled, and could have an impact depending on equipment performance differences from CFC free HVAC equipment, so the impacts of this prerequisite remain an omission.

MATERIALS & RESOURCES CREDITS

“Building material choices are important in sustainable design because of the extensive network of extraction, processing, and transportation steps required to process them. Activities to create building materials pollute the air and water, destroy natural habitats, and deplete natural resources.”[29][p167]

As stated above there are a wide variety of impacts from the material choices made in the design, construction and operation of a building. In order to address these impacts many sectors of the building industry have developed products, services and new practices. While by no means standard practice, these “environmentally friendly” material strategies are becoming more widespread. There are materials available, which incorporate industrial and consumer wastes (such as flyash concrete, recycled plastic lumber, engineered wood products) to minimize both natural resource depletion and end of life impacts. There are also materials available that use more environmentally benign resource inputs from the beginning (such as certified “sustainable” woods, wheat straw boards, bamboo flooring). Further efforts are targeted towards improving longevity of existing materials through building reuse and salvaging efforts.

The LEED *Materials and Resources* (MR) credit section is designed to promote building design choices that protect natural resources, and minimize the impacts of the construction process. Results from simulations of the MR credits are not necessarily representative of the whole impact of these credits. In particular the protection of primary materials is one of the dominant purposes behind several of the credits in this section. Since this study is only quantifying energy consumption and solid waste impacts, readers should recognize the limits in scope when interpreting results.

MR 2: Construction Waste Management

MR2: Credit Intention

"Divert construction, demolition, and land clearing debris from landfill disposal" and "redirect recyclable material back to the manufacturing process."[29] [p179]

A recent report states that 409,029,000 tons of municipal solid waste (MSW) was generated in the US in 2000, an increase of 7% over 1999 [45]. MSW can include wastes from the following sources: residential, commercial, institutional, construction and demolition, industrial and agricultural sources. According to a 1999 study construction and demolition waste (CDW) in California accounts for 11.6% of the total MSW waste stream [46][p9]. Lawson states that CDW accounts for 33% of the total British waste stream (MSW and sewage) [47] [p148]. The top 3 components of CDW from a recent survey of 19 nonresidential buildings were concrete (66%) wood (16%) and land debris (9%) [2] [p 2/18] all of which can be recycled with sufficient effort. MR2 is intended to both reduce initial waste production and enhance recycling activity. The primary vehicle is a waste management plan. In projects that have instituted waste management plans reductions in CDW have been substantial. For example, in 1993 the city of Portland was able to divert 47% of all construction and demolition debris [29] [p180].

MR2: Credit Structure

There are 2 credit tiers available in MR2. The first is for recycling or salvaging at least 50% (by weight) of "construction, demolition and land clearing waste." The second is for increasing the total to 75%. The calculation of CDW Recycling Rate (CRR) uses equation 1. RR needs to exceed 50% for 1 credit or 75% for 2 credits.

$$\mathit{CDW\,Recycling\ Rate\ [\%]} = \frac{\mathit{Recycled\,Waste\ [tonnes]}}{\mathit{Recycled\,Waste\ [tonnes]} + \mathit{Landfilled\ Waste\ [tonnes]}}$$

Equation 1: Recycling Rate (CRR) calculation

MR2: Credit Calculation Discussion

The CRR calculation provides a simple method of determining the percentage of construction wastes diverted. Currently the credit is based on a mass only calculation. In many cases tippage fees are based on volume, which may create variations in CRR if different density values are used to estimate mass based on the volume. However the LEED reference manual provides some sample densities and any differences are likely to be small. There is no mechanism in this credit for reducing waste generation, since the CRR is simply a fraction of total waste. While a waste management plan would in all likelihood include general waste minimization provisions, this credit mechanism does not explicitly promote this.

MR2: Simulation: Key Parameters

CDW affects the total waste burdens from construction. Construction wastes are typically hauled by truck to a landfill or recycling facility. The key parameters for this simulation are -

- Changes in masses of materials sent to landfill or recycling.
- Changes in energy and waste related to CDW management. i.e. different transport methods or distances.

MR2: Simulation: Methods

In the SWH LCI solid wastes from construction activities is determined based on industry data [48] and estimates (generally 1-5% of installed mass). Total CDW for SWH amounts to 449 tonnes. Materials reused on site (sand, gravel wastes) are not included. All of the CDW is transported by 40-ton truck to a landfill 8 km away[4].

Diverting the recycled mass to reduce total solid waste burdens for the construction phase simulates the CDW recycling process. Recycled materials are assumed to travel in smaller loads, and by smaller trucks, so all the recycled mass transport is modeled with an 8-ton truck dataset. Finally, recycling facilities can be further from the construction site than the landfill, so the

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[4] See the SWH LCA paper for a description of the accounting procedures for landfill materials, in particular the SWH LCI does not include credit for embodied energy changes due to recycled materials, or energy capture through landfill incineration.

transport distance to recycling facility is 50 km (based on Ann Arbor conditions). Thus, in this simulation there is a tradeoff between reductions in solid waste generation and additional energy burdens from less efficient transportation and greater transport distances.

MR2: Simulation: Results

Because all the SWH status quo CDW was originally landfilled, the status quo CRR of SWH is 0%. Three alternative scenarios are modeled with CRRs of 50%, 75% and 100% (224 tonnes, 336 tonnes and 449 tonnes respectively). The first two represent the 1 and 2 point MR2 credit tiers, but it is valuable to examine the additional effects of 100% CRR. Figure 5 illustrates the energy and solid waste effects from the different levels of CDW diversion.

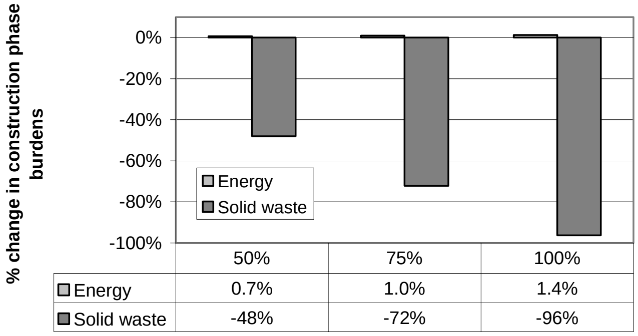

Figure 5: CDW impacts on construction burdens.

Energy consumption increases 20 - 39 GJ and solid waste generation is reduced by 224 - 449 tonnes. Based on these scenarios, the positive impacts of CDW management (solid waste reduction) are far greater than the negative impacts (increased energy consumption). The 100% CRR scenario only increases total construction related energy consumption by 1.4%, while the reduction in construction phase solid waste is almost total[5]. However construction related activities only account for 4.7% and .1% of material placement and total life cycle energy consumption respectively and 16% and 5% of material placement and total life cycle solid waste generation. Further, the LEED reference manual provides a general estimation for CDW of 10-

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[5] The outstanding wastes are those related to construction related energy consumption (diesel fuel and electricity) that are not included as site waste materials.

12kg/m^2. In SWH this would equal only 80 tonnes, so results of the MR2 simulation, limited as they are, may overstate the effects of MR2.

MR2: Analysis

MR2 appears to be effective in providing a means of crediting the diversion of CDW from landfills. However, the impact of this credit in a total life cycle context is marginal. This project is unable to assess construction industry capabilities in order to evaluate the appropriateness of the 50% and 75% CRR threshold levels. It would be valuable to determine what is possible in industry currently and ensure that these thresholds are sufficiently above the norm to represent "green" practices. It is also important that the difference between the 1 and 2 point tiers are significant enough in terms of additional effort to warrant an additional credit point.

MR2: Recommendations

Near Term

- Review current national waste characterizations and CDW recycling trends to document appropriate CDW recycling benchmark thresholds.
- Ensure that the 2 point CRR tier reflects a significant enough advancement over the 1 point CRR tier to warrant a second credit.

Longer Term

- Evaluate options for weighting specific wastes in the CRR calculation to permit the promotion of specific materials recycling/diversion depending on regional priorities or waste prevention strategies.

MR4: Recycled Materials

MR4: Credit Intention

"Increase demand for building products that have incorporated recycled content materials, therefore reducing the impacts resulting from the extraction of new materials."[29] [p191].

In recent years the use of recycled materials has become more popular as a means of improving the environmental characteristics of a building. A recycled material is one in which a portion of it is composed of materials that would have otherwise been disposed of. Examples such as cellulose insulation made from recycled newsprint or concrete with cement being replaced with industrial flyash are increasingly common in the building industry. Recycled materials are generally considered environmentally beneficial for several reasons. Using materials made from waste can reduce landfill burdens; it also displaces the use of finite primary or virgin resources; it also can reduce the embodied energy[6] of the material, by eliminating the extraction and processing energy burdens for the primary materials (although in some cases embodied energy for recycled materials can increase, due to additional or lower efficiency production techniques). Typically recycled materials are classified as post-industrial or post-consumer. Post-industrial materials are defined as waste materials from an industrial process, which have never had a consumer use. Post-consumer recycled materials are those collected after consumer use. LEED and other programs place a higher value on post consumer materials in order to encourage recycling of materials that have served a functional use. While it is desirable to reduce industrial waste streams, environmental advocates are wary of stimulating industry to just maintain wasteful practices, through industrial recycling instead of eliminating or reducing waste generation through improved design.

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[6] Embodied energy here refers to energy required to extract, process, transport and refine materials into a finished product. It does not include the energy required to deliver the material to the building site or construction energy for installation.

MR4: Credit Structure

There are two credit tiers for MR4. One point is earned for "specifying a minimum of 25% building materials that contain in aggregate, a minimum weighted average of 20% post-consumer, or a minimum weighted average of 40% post-industrial recycled content material." A second point is earned if 50% of building materials achieve the required levels of recycled content. Individual materials are given a Recycled Content Value (RCV), which is determined by the cost of the materials (equation 2).

$$Recycled\ Content\ Value[\$] = \left(Material\ Value[\$] * \left[\frac{Post\text{ - }Consumer[\%]}{20\%} + \frac{Post\text{ - }Industrial[\%]}{40\%} \right] \right)$$

Equation 2: Recycled Content Value (RCV) calculation

For assemblies (i.e. assembled products such as windows, or aggregated materials such as concrete) where the incremental costs for the recycled constituent cannot be disaggregated, a total assembly content percentage is calculated (equation 3), which is then used in determining RCV. The sum of each material's RCV is divided by the total project material costs (equation 4) to determine the Recycled Content Rate (RCR), which must exceed 25% or 50% to achieve 1 or 2 points respectively.

$$Assembly\ Recycled\ Content[\%] = \frac{Material\ Weight[lbs] * Recycled\ Content[\%]}{Total\ Weight[lbs]}$$

Equation 3: Assembly recycled content calculation

$$Recycled\ Content\ Rate[\%] = \frac{Recycled\ Content\ Value[\$]}{Total\ Materials\ Cost[\$]}$$

Equation 4: Recycled Content Rate (RCR) calculation

MR4: Credit Calculation Discussion

It is assumed that the cost based method was chosen in order to ease industry adoption, since material costs are well known, but specific masses might not be. Additionally, the USGBC created the RCV calculation to "increase demand" for recycled materials by rewarding or penalizing use of materials with recycled content that is higher or lower than the thresholds. The RCV calculation divides recycled content by thresholds of 20% for post-consumer and 40% for post-industrial recycled content. These thresholds supposedly are the levels at which recycled content is sufficiently high to represent an increase over industry norms. There are several implications of this procedure for calculating recycled content that should be discussed. First, this approach weights more heavily expensive items, an approach that does not necessarily reflect the environmental impacts of a material. Second, multiplying material value by a fixed percentage has significant benefits for materials with high recycled content. While in many cases this is desirable in one notable case it allows a building to achieve LEED credits for status quo construction techniques. Structural steel is generally made in an Electric Arc Furnace, and is composed of about 95% scrap, the majority being post-consumer [49]. Due to the high costs of structural steel in many commercial buildings, when structural steel is included in the RCV calculation the steel alone can yield both MR4 points. While it is true that recycled materials are being used, LEED is intended to stimulate change, and move beyond status quo practices. In this case the calculation method is not supportive of this goal. It should be noted that members of the LEED Technical Advisory Group seem to be aware of this limitation and may address it in future revisions [50]. However, for the present this feature is promoted as a windfall by the Steel Recycling Institute [49], as well as LEED trainers[7].

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[7] During an advanced LEED training workshop [51] the presenter, while recognizing the flaw of this calculation still recommended taking advantage of it. He did, however, mention that the USGBC will consider eliminating credits that are deemed too simple to achieve in the future.

MR4: Simulation: Key Parameters

Recycled materials affect life cycle burdens because of different embodied energy content as well as different amounts of manufacturing waste than their "virgin" counterparts. The key parameters in this simulation are –

- Embodied energy and manufacturing waste of individual recycled materials
- Costs of materials
- Post consumer and post industrial recycled content
- Product equivalence between virgin and recycled materials, especially density

MR4: Simulation: Methods

This simulation is modeled in SWH by compiling a complete materials cost summary (Appendix E) derived from the SWH final billing statement [52]. The total materials cost (excluding equipment, mechanical, electrical materials and labor) for SWH is $5,977,176. Equation 2 is then applied to each existing material with recycled content to determine the status quo RCR (Table 3). As mentioned above the impacts of structural steel are significant.

Material	Material Cost	PC	PI	RCV
concrete work	$568,236		3%	$36,402
wire mesh	$6,000	43%		$12,900
Precast plank	$581,300	1%	3%	$62,025
block material	$114,720		3%	$7,457
Structural Steel	$1,023,528	59%	31%	$3,812,642
Steel Decking	$79,625	20%	10%	$100,328
metal fabs	$528,900	25%		$661,125
Millwork	$242,348		70%	$422,625
Steel Doors and Frames	$25,000	29%		$36,404
Roofing & Sheet Metal, Roof	$90,200		4%	$10,122
metal wall panels	$126,500	25%		$158,125
Sound proofing	$190,000		14%	$68,400
metal studs	$95,656	20%	10%	$120,527
building insulation	$9,600		14%	$3,456
Drywall Glass Fiber Gypsum	$72,330		41%	$73,789
Acoustical Ceilings	$58,502	18%	18%	$78,398
carpeting	$247,168	4%		$52,566
total RCV				$5,717,291
total materials costs				$5,977,176
LEED RCR				**96%**

Table 3: SWH status quo Recycled Content Rate (RCR)

SWH without any effort to incorporate recycled content has an RCR of 96%. An RCR of 63% is achieved based on structural steel content alone. In order to explore the impacts of other recycled materials it is necessary to de-emphasize the contributions of steel. According to LEED guidelines [29] [p.194] steel products for which there is no documentation are assumed to have a 25% post-consumer recycled content. For the MR4 simulations all steel products are therefore set at 25% post consumer content (which alone still yields 40% RCR); this brought the status quo RCR down to 53%, still sufficient for both MR4 points. Since it is impossible to eliminate steel content, this simulation is restricted to exploring the effects of recycled materials which bridge the steel only RCR (40%) to the 2 point 50% RCR. In order to accomplish this certain existing recycled materials were “turned off” to lower the existing RCR. In the SWH LCI [39] millwork[8], gypsum wallboard and fiberglass insulation all have some post-industrial recycled content (70%, 41% and 14% respectively). These three materials were replaced with 100% virgin content materials to bring the total RCR below 50% and allow alternative material configurations to be explored. The “minimum” RCR is 43%. Three combinations of recycled materials are examined to explore the impacts of this credit (Table 4). The first two attempt to simulate a minimum LEED compliance with different recycled materials, each with approximately equal RCR, the third represents a “maximum” recycled option. (See Appendix F for complete RCR tables for options 1-3)

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[8] Millwork includes both particleboard and wood, but since these were indistinguishable in the billing summary they were treated as an assembly for the purposes of determining RCV and the recycled content was calculated with equation 3

	Option 1 **56%RCR**	**Option 2** **53%RCR**	**Option 3** **75%RCR**
Recycled Material Substitutions			
masonry	20% flyash	50% slag	50% slag
precast	20% flyash	50% slag	50% slag
concrete	20% flyash	50% slag	50% slag
carpeting		recycled nylon carpeting	recycled nylon carpeting
insulation	recycled cotton insulation		recycled cotton insulation
flooring	recycled ceramic tile		recycled ceramic tile
finishes	recycled paint		recycled paint
primary material substitutions			
insulation		replace recycled fiberglass with virgin fiberglass	
millwork	replace particle board with primary wood	replace particle board with primary wood	
drywall	replace synthetic gyposum with virgin gypsum	replace synthetic gyposum with virgin gypsum	

Table 4: Recycled material configurations

Possible material choices for this comparison were limited by scarce availability of LCI data on recycled building materials. For this study a set of recycled material LCI datasets from the BEES database [26] of materials was utilized. It should be noted that BEES has recently added several additional recycled material datasets that were unable to be utilized in this study due to limitations in time, but future analysis of MR4 could benefit from the increased material substitution possibilities enabled by these datasets. Further recycled material information was drawn from an unpublished study of recycled cotton insulation [53] (table 5).

BEES Datasets Used		**Recycled Content**	
BEES#	**Description**	**PI**	**PC**
A1030B	20% Flyash Concrete	2%	
A1030F	50% Slag Concrete	6%	
C3012B	Recycled Latex Interior Paint		65%
C3020A	Ceramic Tile with Recycled Windsheild Glass		43%
C3020H	Recycled Polyester Carpet Tile with Traditional Glue		75%
Other Dataset Used		**PI**	**PC**
	Recycled Cotton Batt Insulation	70%	

Table 5: Recycled material, data sources and recycled content

For this study only the material production and manufacturing data from the BEES datasets were used. Since BEES datasets include replacement rates that are different than those in the SWH LCI, inputs and outputs are divided out to determine single unit values[9]. This single unit dataset then follows the same replacement rates that were used in the SWH LCI. The substitution of materials is based on the area covered because of different densities for substitute materials. In some cases this was significant, in others it was marginal (Table 6).

	Tonnes	
SWH material / Substitute Material	**SWH**	**Subs.**
Concrete / 20% Flyash	6569	4317
Concrete / 50% Slag	6569	4784
Nylon Carpet / Recycled Carpet	13	11
Latex Paint / Recycled Latex Paint	7	6
Ceramic Tiles / Recycled Ceramic Tiles	23	28
Fiberglass Insulation / Cotton Insulation	6	7

Table 6: Material mass comparisons

In order to simulate the effects of each option existing materials are "turned off" and substitute materials are "turned on." This affects life cycle burdens in two phases, material placement, due to changes in embodied energy and mass transported (no transport distance differences are modeled for substitute materials), and decommissioning due to changes in recyclability as well as mass transported. Each substitute material is assumed to have equivalent performance characteristics, so replacement frequencies and operational impacts are equivalent. It is unlikely that there is any measurable difference in construction burdens due to the substitution of different materials, but that factor has been omitted.

MR4: Simulation: Results

The largest impact from MR4 occurs during the material production portion of the material placement phase and ranges from a 12% to a 21% primary energy reduction (option1 and option 3 respectively). Transportation impacts during material placement are only slightly affected (6-7% reductions in primary energy). Decommissioning burdens are also slight (3% reduction in primary energy in all cases). Changes in solid waste generation are similarly distributed among

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[9] Barbara Lippiatt, NIST principal author of BEES, confirmed this approach in personal communication.

life cycle phases, except during decommissioning, where a larger proportion of solid wastes were recycled (9-10% reduction). Individual material reductions span a wide range (Table 7) with some even increasing over the status quo. This range is due to the different material masses, differences in material production energy and manufacturing waste burdens and differences in end of life recyclability between the original and recycled materials. For example, recycled ceramic tile requires more material production energy than the existing ceramic tile it is displacing and produces more solid waste, while the recycled nylon carpeting consumes much less energy in production, but generates more manufacturing wastes than the status quo material.

	Change in Energy Cons. (GJ)			Change in waste generation (tonnes)		
Substitute Material	**Mat. Prod.**	**Trans.**	**Decom.**	**Mat. Prod.**	**Trans.**	**Decom.**
50% slag concrete	-5,408	-1,161	0.1	-780	-4	0
20% flyash concrete	-4,835	-1,490	0.1	-772	-5	1
Recycled nylon carpeting	-4,573	-7	0.0	85	0	-4
recycled paint	-808	-11	0.0	5	0	-17
replace recycled fiberglass with virgin	6	0	0.0	0	0	0
replace synthetic gypsum with virgin	60	0	0.0	6	0	0
replace recycled millwork with virgin wood	79	0	0.0	0	0	0
recycled cotton insulation	111	1	0.0	3	0	1
recycled ceramic tile	227	18	0.0	2	0	0

Table 7: Individual material impacts

There is little correspondence between the LEED RCR and the measured environmental impacts. Option 2 with a lower RCR (53%) than option 1 (56%) has a greater reduction in energy and solid waste burdens (Figure 6). Energy reductions in Option 2 are almost equivalent to Option 3, which has a much higher RCR (75%). In terms of total life cycle impacts all three options only accounting for a .5% reduction in life cycle energy consumption but 8-9% reductions in life cycle solid waste generation.

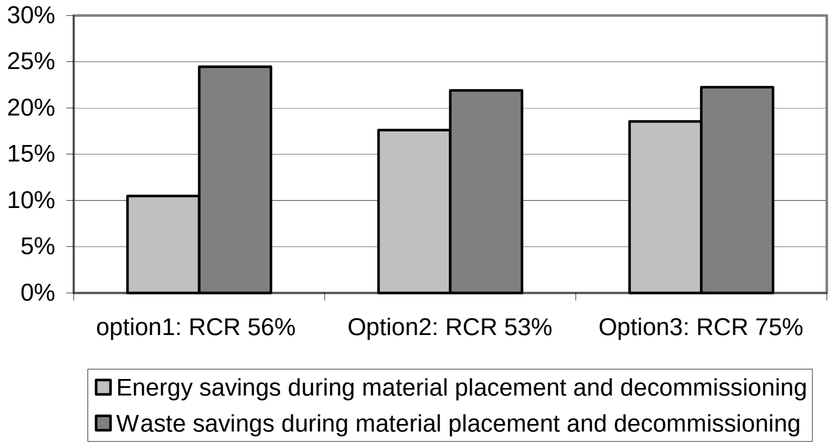

Figure 6: Cumulative energy and waste reductions during material placement and decommissioning

MR4: Analysis

The apparent discrepancy between LEED cost based RCR and the measured environmental impacts is significant (Table 8). For example the contribution of the 50% slag concrete in Option 2 is responsible for 57% of the energy savings and 94% of the waste reduction, but only accounts for 6% of the RCR. There is no apparent relationship between the cost influence of these materials in achieving LEED credits and the environmental benefits measured in this study.

	opt.	%RCR	% energy savings	% waste savings
50% slag	2	6%	57%	94%
20% flyash	1	2%	92%	83%
recycled nylon carpeting	2	16%	41%	-10%
recycled paint	1	5%	12%	1%
cotton insulation	1	10%	-2%	0%
recycled ceramic tile	1	9%	-4%	0%

Table 8: Comparison of RCR contributions and proportional energy and waste impacts

It can be argued that the primary intention of MR4 is to conserve valuable natural resources and divert materials from waste streams. Therefore measurements of energy and solid waste inadequately represent the benefits of MR4. However, several points mitigate this argument. The availability of recycled materials for buildings appears to concentrate on higher cost and lower mass items, which makes it easier to achieve a high RCR, but does not correspond to higher environmental benefits. Further, many available recycled materials are replacing materials that are not particularly scarce such as glass, gypsum and cement. Therefore the resource preservation argument needs to be considered in context of actual resources being conserved. Waste prevention is clearly a concern, and the contributions of building products to the waste stream has already been discussed, but from this case study it appears that the LEED RCR calculation does not promote waste reduction in material selection. Use of recycled concrete because of its high mass accounts for 80-90% of the waste reduction but because of its relatively low cost only accounts for 2-6% of the RCR. In the case of concrete, benefits during transportation alone exceeded all potential benefits for recycled paint or recycled cotton insulation. Finally, in this case study the dominance of steel products in the RCR calculation points to a serious limitation in this credit. The entire spectrum of this examination focused on a narrow band between the minimum practical RCR from steel alone and achieving the LEED RCR of 50%. It is true that steel has a high recycled content, but LEED is not designed to award points for good practices that are already industry norms.

MR4: Recommendations

Near Term

- Isolate steel products for RCV calculations. Set the baseline for the RCV for steel products above existing industry norms, so that only steel products that exceed industry norms are rewarded.
- Eliminate the cost based calculations. Material costs are not reflective of environmental benefits. A mass based calculation would create a credit that more accurately reflected the environmental benefits.

Longer Term

- Research industry practices and emerging material characteristics to create material specific baselines for recycled content. For example, if 10% recycled content in concrete represents a reasonable target for industry advancement, then an RCR baseline of 10% for concrete would put it on more equal footing with products which can achieve higher recycled rates more easily, reflecting better each material's potential environmental contributions.

MR5: Local/Regional Materials

MR5: Credit Intention

“Increase demand for building products that are manufactured locally, thereby reducing the environmental impacts resulting from their transportation and supporting the local economy.” [29] [p197].

The effects of transportation on fossil fuel consumption and the resulting pollution are well established [54]. The construction of buildings requires large masses of materials to be transported over great distances, which impacts not only air pollution and consumption of fossil resources, but also infrastructure maintenance and road safety. Additionally it can be generally desirable to reduce the radius of economic influence to support regional economies, promoting local industries and supporting local tax bases. MR5 differentiates between regionally manufactured and regionally extracted materials, awarding credits for reducing first the manufacturing distances on a project and secondly reducing the extraction/harvesting/recovery distances. This distinction is important, since in many cases it is the raw materials that are traveling the greatest distances to regional manufacturing centers.

MR5: Credit Structure

MR5 is a two tiered credit, with 1 point being awarded for specifying a “minimum of 20% of building materials that are manufactured[10] regionally within a radius of 800 km (500 miles[11]).” A second point is available for specifying that of those 20% materials manufactured locally a “minimum of 50% are harvested, extracted or recovered within 800 km of the project” [29][p197].

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[10] “manufacturing refers to the final assembly of components into the building product that is furnished and intsalled.”[29][p 197]

[11] The LEED reference manual uses miles, but for consistency all units are converted to SI.

MR5 uses the same cost based total materials list from MR4. In order to calculate the Local/Regional Manufacturing Rate (MFR) equation 5 is used. The total material costs (excluding labor and equipment) of individual products that are manufactured within 800 km each contribute to the local/regional manufacturing cost (MC).

$$\textit{Local Regional Manufacturing Rate[\%]} = \frac{\textit{Local Regional Manufacturing Cost[\$]}}{\textit{Total Materials Cost[\$]}}$$

Equation 5: Local/Regional Manufacturing Rate (MFR)

To calculate the Local/Regional Extraction Rate (ER) equation 6 is used. The Local/Regional Extraction Cost (EC) uses the total material costs (from the MC) of individual products, which are extracted within 800 km.

$$\textit{Local/Regional Extraction Rate[\%]} = \frac{\textit{Local Regional Extraction Cost[\$]}}{\textit{Local Regional Manufacturing Cost[\$]}}$$

Equation 6: Local/Regional Extraction Rate (ER)

MR5: Credit Calculation Discussion

There is no calculation for assemblies that combine materials extracted within and outside a 800 km radius, so it is unclear how to handle assembly materials. Similarly to the RCR calculation from MR4 the ER and MFR calculations by being cost based reward expensive items. Additionally the single radius of 800 km is an artificial constraint, which as will be discussed below is not representative of material flows in the construction industry. The nesting of the ER calculation within the MFR calculation produces another problem. As illustrated in Table 9 below, it may be more “beneficial” to do less. By specifying the minimum possible MFR, achieving the ER is easier to accomplish, and as demonstrated, in some cases the net result (on a cost basis) can be less, but more LEED points are achieved.

Ex.1: lower results but more LEED pts			
	$	**Mfg<800***	**Ex<800****
product A	$500	$500	$500
product B	$500	$500	
product C	$1,000		
product D	$1,000		
product E	$2,000		
total cost	$5,000	$1,000	$500
		20%	50%
LEED pts		**1**	**1**

Ex.2: higher results but less LEED pts			
	$	**Mfg<800***	**Ex<800****
product A	$500	$500	$500
product B	$500	$500	
product C	$1,000	$1,000	
product D	$1,000		
product E	$2,000		
total cost	$5,000	$2,000	$500
		40%	25%
LEED pts		**1**	**0**

*Mfg<805 = items manufactured within 805 km

**Ex<805 = items extracted within 805 km

Table 9: Example of ER and MFR calculation discrepancy

MR5: Simulation: Key parameters

Material mass and distance to manufacturing facility or site are the key aspects of transport related impacts. The key parameters for this simulation are –

- Cost of materials
- Mass of materials
- Distances traveled from manufacturing facility to site
- Distances traveled from place of extraction to manufacturing facility

MR5: Simulation: Methods

In the SWH LCI transportation impacts are determined based on manufacturer locations and transport methods for the largest mass items. In the SWH LCI manufacturing locations and transportation methods for 96% of the life cycle mass of the building are specifically accounted for. The remaining mass is assigned a generic transport distance of 480[12] km. All of the building materials with available information are delivered from manufacturer to site by truck, the remaining material is also assumed transported by truck (please refer to the SWH LCI for a complete description of transport methodology). In the datasets used extraction related transport impacts are embedded in the material production datasets [55].

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[12] Based on the SWH LCI, in which a generic transport distance of 300 miles (480 km) for all materials of unknown transport distance was assigned.

The approach of the MR5 credit simulation is to explore the difference in impacts from transporting materials with equivalent MFR and ER values but with different masses. Materials are identified as either Low Mass High Cost (LMHC) or High Mass Low Cost (HMLC). Concrete is selected as the HMLC material. Millwork, paint, glazing and carpeting are selected for the LMHC materials. Only the initial installed mass plus site losses are used in this simulation (Table 10).

Low Mass High Cost (LMHC)					
	Manufacturing Rate			Extraction Rate	
materials	cost	tonnes		cost	tonnes
Millwork	*$242,348*	*17*			
paint	*$76,591*	*7*			
carpeting	*$247,168*	*13*			
glazing	*$707,790*	*51*		$707,790	51
MC (all above)	$1,273,897	87			
Total Costs	$5,977,176		**MC**	$1,273,897	
MFR	**21%**	**87**	**ER**	**56%**	**51**

High Mass Low Cost (HMLC)					
	Manufacturing Rate			Extraction Rate	
materials	cost	tonnes		cost	tonnes
MC (concrete alone)	$1,264,256	6486		$682,956	5536
Total Costs	$5,977,176		**MC**	$1,264,256	
MFR	**21%**	**6486**	**ER**	**54%**	**5536**

Table 10: Manufacturing rate (MFR), extraction rates (ER) and masses for LMHC and HMLC scenarios

For the MFR credit the transport distances for either the HMLC or the LMHC are adjusted. The status quo distance for the HMLC is 55km and the status quo distance for the LMHC is 483km. Distance changes are linked to the transportation portion of the SWH LCI. Since extraction related transport impacts are bundled into existing material datasets and the scope of this project precluded researching individual material extraction distances[13], an average extraction impact is created. This average impact is based on combined impacts from truck, rail, sea and river. A baseline distance for HMLC and LMHC was established (160 km and 3220 km respectively[14]) and then increases or reductions from the baseline extraction distance produced

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[13] Except for concrete where some confirmation of average distances from point of extraction to manufacturer was provided by Terry Collins of the Portland Cement Association [56]

[14] 100 and 2000 miles respectively. 100 miles is based on Collins [56], and 2000 miles was an estimate to encompass a national scale.

either positive or negative effects. Extraction impacts are recorded in the material production period of material placement, not the transportation phase, since the original extraction burdens are bundled into the material production datasets. While information is available for the extraction distances of concrete and thus a baseline of 160 km is reasonable, the estimate of a 3220 km baseline for LM materials is speculative. However a sensitivity analysis of the life cycle impacts of different LMHC baseline extraction transport distances indicates little effect over a range equivalent to half the globe.

MR5: Simulation: Results

Since the status quo MFR of SWH is 79%, sufficient for 1 point, there is no practical way to determine the status quo ER. A profile of impacts relative to SWH status quo transport impacts[15] across a range of distances (all within 800 km) are presented in figures 7, 8, 9 and 10.

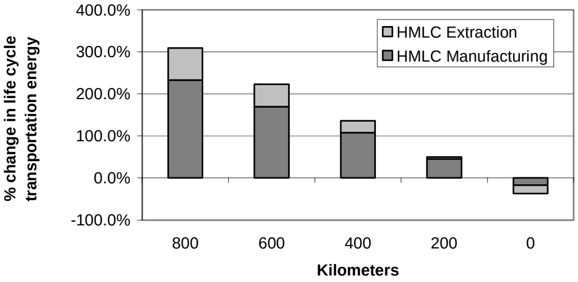

Figure 7: HMLC transport energy impacts

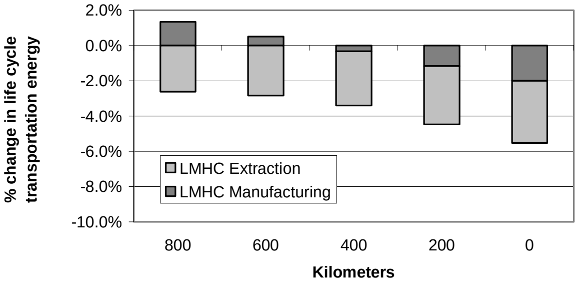

Figure 8: LMHC transport energy impacts

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[15] Even though the extraction impacts are recorded in the material production phase, it seemed appropriate to display their relative impacts against transportation.

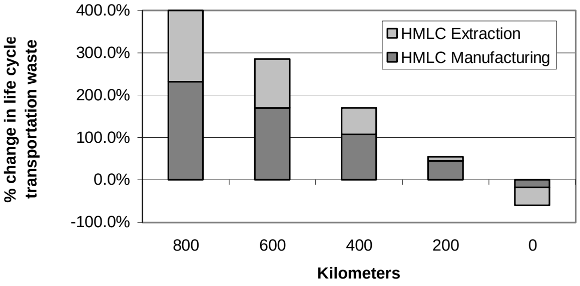

Figure 9: HMLC transport waste impacts

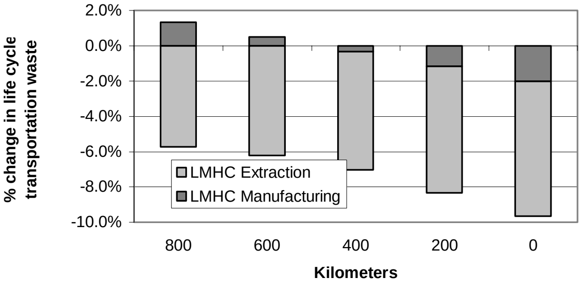

Figure 10: LMHC transport waste impacts

These figures demonstrate that not only are there extreme differences in impacts based on the mass of the materials transported, but the low mass items are relatively insignificant in impact regardless of distance, whereas high mass items quickly generate significant impacts over short distances. Manufacturing and extraction related impacts are similarly scaled depending on the mass of the material, such that a small change in the HMLC material extraction distance exceeds any possible benefits of a LMHC manufacturing distance improvement. It is important to note in these figures that all options fall within the range of acceptable distances for the manufacturing and extraction related credits.

In terms of relative impacts against the SWH total life cycle, this credit has very limited effect. With respect to the impact of transporting the HMLC materials, the outside distance of 800km increases both life cycle energy and waste only 0.4%. If the construction site were sitting adjacent to a concrete manufacturer that was built on top of mines for all the necessary materials, it would still only reduce both life cycle energy and waste impacts by 0.04%. The LMHC materials are an order of magnitude less relevant over greater distances than the HMLC materials.

MR5: Analysis

The impacts of reducing transport distances for the LMHC items from significantly above the 800km threshold is minimal. However, in current practice the HMLC material (concrete) is almost never transported over 800 km, generally coming from a radius of 150-300 km [56]. Based on these results the 800 km radius is an inappropriate threshold, ineffective for either low mass or high mass materials. In some cases obtaining materials from within an 800 km radius could lead to an increase over status quo impacts rather than a decrease. For high mass materials, which do often come from greater distances (steel for example), it is beneficial to consider the relative transport distances, but also impacts within 800 km are significant and an artificial boundary does not address these impacts. Transportation impacts are almost strictly mass and distance related (equipment efficiency has some role). To construct a credit system that ignores this effect undermines the intention of the credit. Since the majority of building materials in this case study came from well within the 800 km boundary the credit would have offered little in the way of incentive to improve status quo practices. Further the cost based calculations can promote a false impression that materials of low mass which have been selected because they are manufactured or extracted from a closer distance are providing an environmental benefit which, within the boundaries of this case study, does not appear to have merit.

While this project does not include an economic analysis it is worth mentioning that the economic motivations of this credit do not seem to be supported in current application. While promoting local economic development is potentially a positive goal, a radius of 800 km can span more than one state jurisdiction and certainly can exceed local municipalities. At that scale it becomes questionable whether or not this distance is actually discriminatory against other national or international manufacturers, with no corresponding regional benefit. This boundary also raises the question, as states and public agencies adopt LEED standards, whether or not this credit contradicts federal interstate commerce protections.

MR5: Recommendations

Near Term

- Set an independent threshold for achieving the extraction credit so those projects that specify high levels of locally manufactured goods are not at a disadvantage in achieving the second tier (the extraction credit) against projects that meet the minimum requirements for locally manufactured goods.
- Review the emphasis on local economic benefits; it is unsupported in the current form of MR5.

Longer Term

- Replace the cost based MFR and ER calculations with mass based calculations. Make the mass based calculations sensitive to individual material standards of practice. For example a combined kgkm threshold could represent an aggregate of average building material distances and masses, scalable by total building square footage and structural composition (i.e the average kgkm for steel framed buildings and concrete are not necessarily comparable).

ENERGY AND ATMOSPHERE CREDITS

“Buildings in the United States consume greater than 30% of the total energy load and about 60% of the nation’s electricity. Fossil fuels are used to produce about three-quarters of our energy production. The use of fossil fuels such as oil and coal requires extraction, refining, power generation, and distribution, significantly impacting the environment.”[29][p93]

Due to the long life span of a building, decisions about operational characteristics made in the design of a building have environmental impacts that will accrue for decades. Downstream effects from power production such as global warming and acid rain are well documented. Upstream effects such as ecosystem degradation from resource extraction are also well established. Similarly, relatively simple efforts made in the design stage can reduce those impacts dramatically. While energy conservation has been long recognized as an important factor in building performance [8] there is still much room for improvement.

LEED attempts to address these issues through the *Energy and Atmosphere* credits. By first establishing the prerequisites of fundamental building commissioning, minimum ASHRAE 90.1 energy standards and CFC reduction in HVAC equipment, LEED attempts to establish a baseline performance standard. From there specific credits reward higher levels of energy performance, incorporation of renewable site power, use of renewable utility power, further refinements to building operational standards and further ozone protection.

EA1: Optimize Energy Performance

EA1: Credit Intention

"Achieve increasing levels of energy performance above the prerequisite standard to reduce environmental impacts associated with excessive energy use."[29][p117]

Energy consumption is the impact most often associated with buildings, and according to some the best addressed [8]. Buildings are responsible for 38% of U.S. energy consumption [1] [Table 2.1a]. While much attention has been paid to energy efficiency in buildings there is still much more room for improvement. Given the long operational lifespan of most commercial buildings the benefits, both economic and environmental, of improved performance can be substantial.

EA1: Credit Structure

EA1 has the most points available of any LEED credit. One to ten points are available depending on the level of energy performance projected. The credit procedure is to "reduce Design Energy Cost (DEC) compared to the Energy Cost Budget (ECB) for regulated components as described in the requirements of ASHRAE/IESNA Standard 90.1 1999, as demonstrated by a whole building simulation using the Energy Cost Budget Method." [29] [p117]. The ECB is based on an energy model using minimum standards for an ASHRAE 90.1 compliant building. The DEC is based on an energy model using the proposed design and modeled according to a combination of ASHRAE 90.1 section 11 guidelines and the LEED Energy Modeling protocol. The ASHRAE modeling guidelines are intended to ensure that the ECB and DEC are equivalent except for design changes. Energy costs for the calculations are based on either local utility rate schedules, ASHRAE adopted rate schedules or the LEED reference manual [p129]. Regulated components are defined as heating, cooling, auxiliaries (pumps, fans, etc.), water heating and interior lighting. Non-regulated components are plug loads, process energy, garage ventilation, exterior lighting, elevators and other miscellaneous energy.

Points are awarded based on a building’s Energy Savings Percentage (ESP), which is calculated in equation 7 and correlates to LEED points for a new construction according to Table 11.

$$\%\ Savings = 100 * \frac{ECB - DEC''}{ECB}$$

Equation 7: Energy Savings Percentage (ESP) calculation

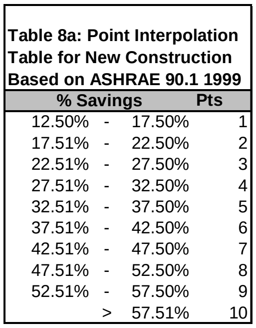

Table 8a: Point Interpolation Table for New Construction Based on ASHRAE 90.1 1999

% Savings			Pts
12.50%	-	17.50%	1
17.51%	-	22.50%	2
22.51%	-	27.50%	3
27.51%	-	32.50%	4
32.51%	-	37.50%	5
37.51%	-	42.50%	6
42.51%	-	47.50%	7
47.51%	-	52.50%	8
52.51%	-	57.50%	9
	>	57.51%	10

Table 11: ESP points table for new construction

ECB and DEC are building load multiplied by energy price (Equation 8 and 9). DEC″ is DEC with any Renewable Energy Contribution (REC[16]) subtracted (Equation 10).

$$ECB = (Baseline\ kWh * kWh\ Cost[\$]) + (Baseline\ Therms * Therm\ Cost[\$]) + (Baseline\ Other\ Energy[\$])$$

Equation 8: Energy Cost Budget (ECB) calculation

$$DEC = (Proposed\ kWh * kWh\ Cost[\$]) + (Proposed\ Therms * Therm\ Cost[\$]) + (Proposed\ Other\ Energy[\$])$$

Equation 9: Design Energy Cost (DEC) calculation

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[16] See credit EA2 for a explanation of REC

$$DEC'' = DEC - REC$$

Equation 10: Design Energy Cost (DEC″) calculation

EA1: Credit Calculation Discussion

Whole building energy modeling is a topic beyond the scope of this project. The complications in accurately modeling an entire building, especially the HVAC systems, generally require an engineer with many years experience. Even under ideal conditions the margins of error can be significant [57], [4]. The SWH base case model (SWH BC) and the ASHRAE 90.1 minimum compliance model (ASH MC) hopefully represent an adequate representation for the purposes of this analysis. However future refinements could address the quality of the energy models used.

The choice to exclude non-regulated loads may be based on industry practices, or complexities in approximating these loads, however their exclusion does inflate the currently defined LEED ESP, creating a gap between LEED ESP and actual savings in the current program format. If unregulated loads were included in the calculation, opportunities to reduce consumption in these loads could present themselves, however under the current format there is no incentive to reduce these loads.

Nall has articulated several limitations in using ASHRAE 90.1 as a standard for energy performance measurement [58]

> “[ASHRAE 90.1] is designed to regulate the performance attributes of certain components that are used in buildings…it also imposes…reasonable limits upon designs with respect to certain performance parameters that are the result of design rather than component selection…It imposes no regulation whatsoever on building and system design as long as the components meet the statutory requirements and these few specific design limitations are met.”

The use of a prescriptive energy standard that focuses on component selection and not the total performance of the building could lead to “gaming” the modeling process in order to achieve results, rather than rewarding the design of high performance buildings.

Another problematic aspect of the EA1 calculation is that changes in the price of a specific energy type alters that energy type's fractional contribution to ECB and DEC in a way that appears imbalanced. For example an increase in electric prices decreases the amount of electric reductions needed to achieve a given ESP, and correspondingly reduces the actual energy savings achieved (Table 12). This calculation method creates inequities in demand reduction requirements for achieving EA1 depending on regional energy pricing. Additionally it creates a loophole where a LEED user would benefit from documenting the highest possible energy pricing to reduce their requirements, regardless of long-term price conditions.

electric price $/kWh	**% elec. Reduction for 1 LEED pt.**	**Life span GJ saved**
0.04	21%	215,669
0.07	18%	184,859
0.10	16%	164,319

Table 12: The impact of electric pricing on LEED ESP and actual energy savings

EA1: Simulation: Key Parameters

While it would be ideal to explore tradeoffs between material and system choices that impact operational performance, such an analysis is beyond the scope of this project. The calculation of change in material composition or system configuration to yield a specific change in performance puts the already limited accuracy of the energy models into even more speculative realms (for an interesting evaluation of this kind see Lee [59]). As a result the analysis of EA1 will be limited to modeling energy consumption for the ASH MC scenario, proportional reductions according to Table 9 and comparisons to the SWH BC energy consumption. The key parameters for this simulation are –

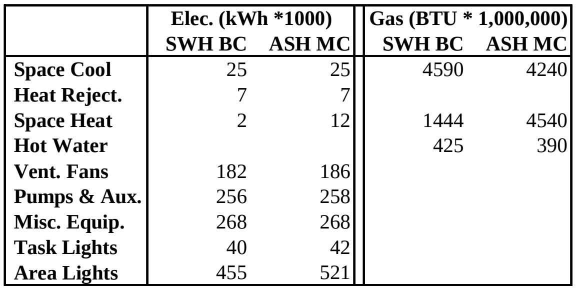
- SWH BC energy performance
- Parameters of ASHRAE 90.1, 1999 required to generate ASH MC
- ASH MC energy performance

EA1: Simulation: Methods

In order to develop ASH MC, a duplicate of the SWH BC is adjusted to reflect the ASHRAE 90.1 1999 guidelines [60] (See appendix G for tables of changes between the two models). For this building type ASHRAE stipulates a total average lighting power density of 16.4 watts/m^2, an increase over the 15.1 watts/m^2 found in SWH. ASHRAE stipulates a higher efficiency for the cooling and the hot water systems than SWH, while SWH matches the ASHRAE minimum for heating system efficiency. The ASHRAE minimum U-values and C-factors for doors, windows, walls and roofs are all higher than the SWH base case. Only the ASHRAE U-value for mass floors is lower than what is found in SWH. The ASH MC site demands are substituted in the SWH LCI model to determine operational burden changes. A final step involves simulating life cycle demand changes for meeting various credit thresholds. The energy inputs are structured to enable incremental reductions in total electric or gas consumption. While not modeling specific feature reductions (like lighting, pumps etc.), only total source reductions, this approach does allow for comparisons between impacts from overall energy reductions and specific energy type reductions.

EA1: Simulation: Results

Energy consumption for SWH BC over the building life cycle is 2,300,000 GJ. For ASH MC life cycle energy consumption is 2,600,000 GJ, an increase in total life cycle primary energy consumption of 12%. Table 13 illustrates the sources and amounts of annual site energy demands between the two models.



	Elec. (kWh *1000)		**Gas (BTU * 1,000,000)**	
	SWH BC	**ASH MC**	**SWH BC**	**ASH MC**
Space Cool	25	25	4590	4240
Heat Reject.	7	7		
Space Heat	2	12	1444	4540
Hot Water			425	390
Vent. Fans	182	186		
Pumps & Aux.	256	258		
Misc. Equip.	268	268		
Task Lights	40	42		
Area Lights	455	521		

Table 13: SWH BC and ASH MC annual energy consumption

Most of the differences between the two models are minor, space heating and area lighting accounting for the majority of the difference. While ASH MC equipment efficiency improvements over SWH BC for hot water and cooling account for the improved performance of these systems, the envelope performance reductions are responsible for the large increase in space heating burdens. According to equations 8 and 9 and utilizing local energy prices ($0.07/kWh electric, $0.31/CCF gas)[61] the ECB for the ASH MC is $101,310 ($27,870 gas and $73,440 electric). The DEC″ for SWH BC is $87,290 ($19,630 gas and $67,660 electric), thus according to equation 7 the ESP for SWH BC is 14%, which would qualify for 1 point.

Results of an incremental reduction in total site energy demand, electric-only demand and gas-only (heating and cooling) demand are presented in figures 11 and 12. These figures illustrate the energy savings and energy-related solid waste reductions through demand reductions in a balanced electric and gas reduction, an electric only reduction and a gas only reduction. Each scenario consists of the minimum required reduction in site demands to achieve a LEED point at each successive level. These examples only extend to 4 points because that is where a 100% reduction of the gas demand is required.

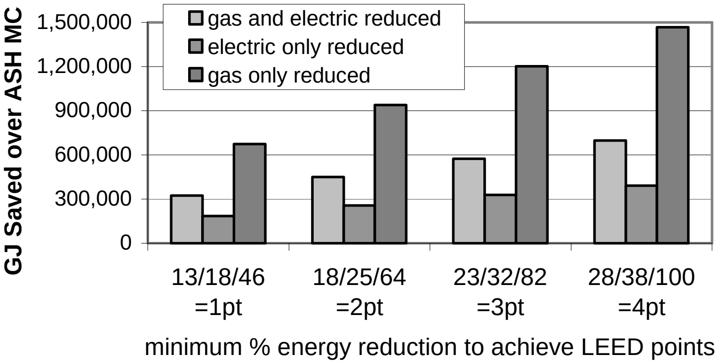


Figure 11: Demand reductions for LEED credits and lifespan energy impacts

The balanced electric and gas reduction scenario matches the LEED ESP thresholds for credits (table 11), that is a 13% reduction in demand equals a 13% ESP. Due to differences in energy pricing, reductions in electric-only or gas-only do not have equivalent demand reduction thresholds for the same LEED points. For example an 18% reduction in electricity would result in 1 LEED point, but gas would require a 46% reduction. This is because electricity accounts for 72% of the ECB, so a much greater reduction in gas is required to achieve the same point as for electricity. However greater reductions in demand do equate to greater primary energy savings, creating a stark difference in primary energy savings versus LEED points awarded for different energy types. In SWH electricity accounts for 41% of primary energy and heating and cooling gas accounts for 58% (the remainder is for water services). So the large reductions in gas demand required to achieve LEED points would produce substantially greater reductions in total primary energy consumption.

Solid waste reductions are similarly linked to energy type, but with different results. Since electricity has a much higher amount of solid waste generated per MJ of power delivered than natural gas, smaller reductions in electric consumption yield greater reductions in solid waste generation than natural gas. For example an 18% reduction in electric demand reduces solid waste generation almost as much as a 100% reduction in natural gas demand.

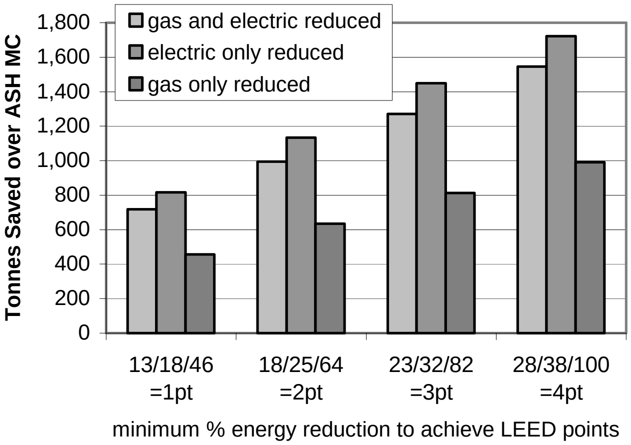


Figure 12: Demand reductions for LEED credits and lifespan solid waste impacts

A final approach to these scenarios is to normalize the results on a per LEED point basis (Figure 13). In each case there is a declining actual energy savings with each subsequent LEED point due to the initial 1-point 12% threshold being a larger step than subsequent point thresholds. Gas has the greatest energy savings per point.

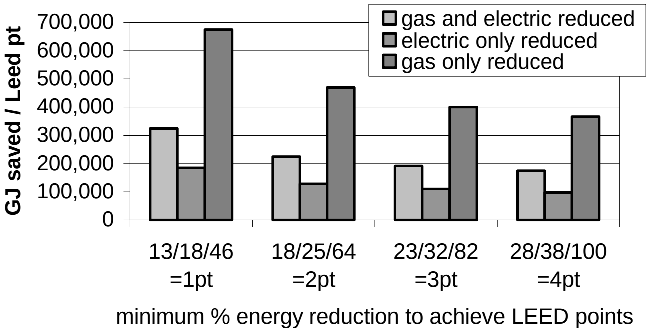


Figure 13: Per LEED point life span energy savings based on different demand reductions

EA1: Analysis

Site demand reductions are generally beneficial, however there are differences in benefit depending on the energy type reduced; currently EA1 does not distinguish between energy types. This is particularly important since users of LEED will most likely select energy reduction strategies that yield the most points, not those that have the greatest environmental benefit. Reductions based on EA1 also do not reflect other impacts that are linked to energy type such as solid waste. Since the intention of this credit is to reduce overall environmental impacts from energy production the ESP should reflect the impact reduction (primary energy consumption and other impacts) not the site demand reduction.

Locking the ESP into regional energy pricing further disassociates the demand reduction from the actual energy savings and raises issues about comparability of buildings in different electric pricing regions. A building owner may be more interested in the economic impacts of energy demand reductions, and for that reason an economic calculation is understandable, however as demonstrated above the economic calculations in EA1 create imbalances that favor reductions in high priced energy demand sources, regardless of their actual energy savings. This structure is a reverse incentive at odds with the program's goals.

A final note about EA1: SWH BC as modeled consumes 12% less energy over the building life span than ASH MC. As far as the authors know there was no attempt to make SWH "energy-efficient." As with other credits EA1 is intended to award practices beyond the status quo. If industry practice currently exceeds ASHRAE 90.1 to such a degree that many buildings would receive EA1 credits without a change in practice, then the standard needs to be reconsidered as an appropriate baseline.

EA1: Recommendations

Near Term

- consider a single energy-pricing schedule for all LEED certified buildings to ensure comparability.
- Reconsider the site demand based ESP calculation. Reflect actual savings by converting site demands to actual demands by utilizing regional primary energy conversion factors for individual energy source types.

Longer Term

- Review the applicability of ASHRAE 90.1 as the energy standard by which credits are measured, both from a technical perspective (i.e. does it actually measure performance) and from an industry norm perspective (i.e. does it represent a good baseline).

EA2: Renewable Energy

EA2: Credit Intention

"Encourage and recognize increasing levels of self-supply through renewable technologies to reduce the environmental impacts associated with fossil fuel energy use."[29] [p135]

According to LEED the use of on site renewable energy production is considered "superior to conventional energy sources" because of its "high coefficient of utilization" and "absence of transportation costs and impacts." Due to the combination of rising energy prices, lowered costs (through improved technology and manufacturing processes) and increased consumer demand, manufacturers of renewable energy systems have seen exceptionally strong growth in the past decade (700% for PV and 900% for wind)[62].

Still, the costs of site renewable power remain a significant barrier, especially since connecting to utility power, in most cases, requires little up front costs or maintenance requirements. Since a building scale renewable power system can run into the hundreds of thousands of dollars, which might only provide basic economic payback over the life span of the building, owners are often reluctant to consider renewable power. However with recent problems and price fluctuations in regional energy markets and new state incentives, renewable power is becoming more attractive. Finally, as fossil resources become increasingly scarce and (in the case of the United States) international in location, renewable energy becomes a potentially important feature of national energy security. Currently, acceptable forms of renewable power generation include solar, wind and biomass.

EA2: Credit Structure

EA2 has 3 tiers based on the fraction of renewable power supplied by the system. One, two and three points are available for demonstrating a Renewable Energy Percentage (REP) of 5%, 10% and 20%, respectively, of the building's annual Design Energy Costs (DEC). Determining REP involves several steps. In order to calculate the REP it is essential to have calculated DEC from EA1. The output of the renewable system can be predicted using any of a number of tools, but the prediction must include actual hourly site conditions that affect renewable system performance (insolation[17], shading, temperature, wind speed, etc.). Based on the renewable system energy output, the value of the Renewable Energy Contribution (REC) is determined using a “virtual” rate based on rates for energy displaced by the renewable energy production. For example, a solar or wind system displaces electricity, so the value of the renewable energy is the amount of energy produced multiplied by the cost of electricity. This virtual rate must use the same rate schedules from EA1. REC is then subtracted from DEC to yield DEC$''$ (Equation 10). The LEED reference manual states this is done because “the ECB method is based on energy that crosses the property line.”[29][p143] and renewable energy is produced on site. The Renewable Energy Percentage (REP) is then calculated using equation 11.

$$\textit{Renewable Energy [\%]} = 100 * \frac{REC}{DEC''}$$

Equation 11: Renewable Energy Percentage (REP) calculation

EA2: Credit Calculation Discussion

There are two factors in this calculation that are problematic. First the exclusion of unregulated loads (see the EA1 credit structure and calculations discussion sections), while perhaps practical, does reduce the percentage of building load met by the renewable energy system. In SWH regulated loads are 90% of the total load, so the fraction of regulated loads required to meet the target REP is lower than the fraction that would be needed to meet the total load. More importantly, the DEC$''$ calculation leads to a lower actual contribution to achieve the desired target REP because DEC$''$ deducts REC, reducing the denominator. For example, in SWH the DEC$''$ for a 5% target REP is 95% of the DEC (it becomes a greater difference the greater the renewable contribution). These two factors combine to yield a total renewable contribution lower than the LEED credit amount, both in energy cost and energy contribution. It is understandable to base the calculations on cost of energy, since total cost is more relevant to building owners than percentage of energy being met, and there may be pragmatic reasons to

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[17] Incident solar radiation on a horizontal plane

exclude unregulated loads (difficulties in estimation being the most obvious reason). However, a motivation for the DEC″ calculation is not apparent. DEC″ is being defined as DEC minus the loads that the renewable energy is meeting, an approach that may be appropriate for determining ESP under EA1. However, calculating REP as REC over DEC″ is double dipping, since the REC is already being accounted for by canceling out some of the DEC load[18]. An extreme example highlights this issue. If the target REP is 100%, the DEC″ calculation would require that the REC be half of DEC, thus a 100% REP = 50% DEC. In this case a building could claim, according to LEED, a 100% renewable energy contribution, but only actually be providing 50% of the Design Energy Cost.

Hypothetical Building: 50,000 ft2, Regulated loads = 40kbtu/ft2 elec., 60kbtu/ft2 gas, 5% target renewable rate, displacing only electricity						
elec rate $/kWh	**gas rate $/ccf**	**virtual rate $/kBTU**	**DEC**	**REC**	**DEC"**	**renewable kBTU needed**
Changes in Electric pricing						
$0.04	$0.31	$0.012	$32,564	$1,551	$31,014	132,273
$0.05	$0.31	$0.015	$38,426	$1,830	$36,596	124,866
$0.06	$0.31	$0.018	$44,288	$2,109	$42,179	119,928
$0.07	$0.31	$0.021	$50,149	$2,388	$47,761	116,401
$0.08	$0.31	$0.023	$56,011	$2,667	$53,344	113,756
$0.09	$0.31	$0.026	$61,873	$2,946	$58,926	111,698
$0.10	$0.31	$0.029	$67,734	$3,225	$64,509	110,052
Changes in Gas pricing						
$0.07	$0.20	$0.021	$46,914	$2,234	$44,680	108,892
$0.07	$0.25	$0.021	$48,385	$2,304	$46,081	112,305
$0.07	$0.30	$0.021	$49,855	$2,374	$47,481	115,718
$0.07	$0.35	$0.021	$51,326	$2,444	$48,882	119,132
$0.07	$0.40	$0.021	$52,796	$2,514	$50,282	122,545

Table 14: Sample impacts on renewable requirements

Another calculation factor with an undesirable effect is the use of regional energy pricing for the virtual rate. While understandable from an implementation perspective, this method can lead to different requirements for renewable contribution depending on the region, which complicates the comparison of LEED rated buildings. Results from changing energy prices for a hypothetical building are presented in table 14. The total load of the building is constant regardless of energy pricing and only electricity is being displaced. As the price of electricity increases the energy

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[18] LEED trainers recently stated that this was not only recognized this effect but encouraged applicants to pursue it when seeking LEED certification [63].

contribution required decreases, but if the electricity price remains static and the price of gas rises, the energy contribution needed increases. This effect is due to the fact that LEED only considers the rate of the displaced energy as the virtual rate. In this example, when electric prices change the virtual rate changes, but when gas prices change it does not. The net effect is that for different building owners in different energy pricing regions the requirements to meet this credit can vary significantly, independently of building load.

EA2: Simulation: Key Parameters

Two factors, site renewable resources (available solar or wind resources in this simulation) and life cycle material burdens (fossil energy inputs and solid waste generation) determine the effectiveness of a renewable energy system. The key parameters in this simulation are –

- Site renewable resource variables such as insolation or average wind speed
- System performance such as life span, and energy conversion efficiency
- Renewable system material embodied energies
- Displacement of grid energy production burdens through renewable energy production

EA2: Simulation: Methods

The simulation of EA2 modeled the life cycle effects of two different renewable energy systems – a wind turbine and a building integrated photovoltaic (BIPV) system. Life cycle impacts for each of these systems includes burdens from extraction, production, manufacture and installation of new materials; a reduction in grid-based energy burdens because of energy produced over the life span of the building; and decommissioning burdens from disposal or recycling of the mass of the system. The energy output of a renewable energy system is dependent on the site renewable resources.

Data for modeling these systems is taken from three primary sources. The life cycle fossil energy and waste requirements as well as energy output for the PV system come from Keolian [64]. Life cycle input data (fossil energy and waste from material production) for the wind turbine comes from Schleisner [65]. Use phase energy production data for the wind turbine comes from the Danish Wind Turbine Calculator [66]. For both of these systems use phase maintenance is considered negligible.

For the BIPV a metal standing seam system is simulated. Variables for system performance include insolation, conversion efficiency and life span. Insolation and conversion efficiency are simulated using system performance data from Detroit and Phoenix (annual panel output of 80 kWh/m^2 and 120 kWh/m^2 respectively). Because the slope calculation in the BIPV LCA is being revised[19] no slope effect is considered for this simulation. Extending the number of years of energy output during operations, since material placement requirements are fixed, simulates life span.

Wind turbine material production requirements from Schleisner are based on a utility scale Vestas 500kW turbine. This simulation modeled output based on different site renewable resources using a Vestas 600kW turbine in the Danish Wind Power Calculator. While Schleisner's report includes fixed output data for turbine performance, variable outputs depending on site conditions are an important element of this simulation. Although not the same turbine as in Schleisner, it is assumed that differences are primarily mechanical and material production energy inputs and manufacturing solid waste generation can be considered equivalent[20]. In order to make the utility scale turbine applicable to this study only a fraction of the material production burdens, proportional to the output needs, are assigned to the model. For example, if the site needs are only 5% of the turbine output only 5% of the whole turbine material production burdens are assigned to SWH. The difference in performance characteristics and material production requirements per unit of energy output between a building scale wind turbine and a utility scale turbine may be significant. However, lack of available LCI data prevents the modeling of a smaller turbine.

The variables used in the wind turbine simulation are mean annual temperature, average wind speed and ground roughness[21]. Different outputs resulting from variations in roughness were plotted in three locations with different average annual wind speeds. This provided the basis for performance functions for each of these three variables (Appendix H). Life span, as for the BIPV simulation, is modeled by extending the number of years of energy output, with material production burdens remaining constant.

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[19] Keoleian is revising the slope calculations.

[20] Schleisner confirmed this in personal communication [67].

[21] The roughness class is defined on the basis of the roughness length in metres z_0, i.e. the height above ground level where the wind speed is theoretically zero [66].

For both BIPV and wind, transport, construction and decommissioning burdens are modeled as are other elements of the SWH LCI. Transportation requirements are based on the mass of the system being transported a generic transport distance of 480km (see MR5: Simulation: Methods). In the SWH LCI construction requirements are modeled as a fraction of material production energy, thus additional material production requirements for the renewable energy systems increases construction requirements proportionally. Decommissioning burdens are modeled by adding the mass of the systems to the demolition energy calculations (see the SWH LCI decommissioning section) and accounting for the transport of materials to either landfill or recycling facility.

Based on all the preceding data two models are established that can be scaled to a desired output energy performance, which in turn is derived based on the desired REP. For example, if the target REP is 5% then, depending on the system and the renewable resource variables selected, the model calculates energy output during operations and energy and solid waste requirements for material placement and decommissioning.

While the requirements for EA2 only specify installation of a renewable system at the time of construction, the life span of most buildings should exceed the life span of a renewable system. In the case of SWH the projected life span of 75 years is over three times the projected life span of either renewable system. Two scenarios, a single installation (SI) and a total building life span replacement (LR), of the specified renewable system are explored in this simulation. For the SI scenario the renewable system displaces grid energy only for the single life span and the burdens are those of a whole single system. For the LR scenario the system displaces grid energy for the entire building life span and the burdens are determined by equation 12. While it is probable that in 20-30 years, when a current PV or wind system is being replaced, performance and material requirements will have changed, it is beyond the scope of this project to model such changes.

$$life\ cycle\ RE\ burdens = \frac{building\ life\ span}{renewable\ system\ life\ span} * single\ installation\ RE\ burdens$$

Equation 12: LR scenario Renewable Energy (RE) system burdens

The actual site conditions at SWH are not ideal for either solar or wind systems. The insolation is equal to the Detroit data from Keoleian (3799 kWh/m^2/day). Ann Arbor has an average wind speed of about 7.5 m/sec, but the city location of SWH has a roughness class of between 2 and 3. It is important for this assessment to consider a range of conditions representing high and low performance for both the solar and wind systems even though this implies different geographical locations. The simulations are limited to 4 variations modeled for all three target REPs and with the SI and LR replacement scenarios. The four variations are:

- Low PV – 3779 Wh/m^2/day average insolation, 15 year life span
- High PV – 5733 Wh/m^2/day average insolation, 25 year life span
- Low Wind – 4 m/sec average wind speed, 2 roughness class, 15 year life span
- High Wind - 8 m/sec average wind speed, 0 roughness class, 25 year life span

EA2: Simulation: Results

The SWH energy model predicted a total of 1460 kBTU/m^2 annual consumption (Table 15), of this 125 kBTU/m^2 were unregulated loads (plug loads), leaving 1335 kBTU/m^2.

source	**type**	**kBTU/m^2**
Lighting	electric	231
other	electric	346
heating	gas	256
cooling	gas	628
total		**1460**

Table 15: SWH status quo energy profile

Using regional pricing of \$0.07/kWh and \$0.31/ccf [61] the total DEC for SWH comes to \$87,280. For both wind and BIPV the conventional energy displaced by the renewable system is electricity, therefore the virtual rate equals the electric rate. For an REP of 5,10 and 20%, 59,400, 113,400 and 207,800 kWh annually are needed (Table 16). Because this simulation is based on achieving a fixed target REP and the system is scaled to exactly that size, the amount of energy produced by each system is the same on an annual basis. For the LR scenarios this means that over the building life span each system produces exactly the same energy. For the SI scenario the amount of energy produced varies according to the life span of the system.

total kbtu/m^2	1335		
DEC	$87,287		
target RE%	**5%**	**10%**	**20%**
DEC"	$83,131	$79,352	$72,739
REC	$4,157	$7,935	$14,548
virtual rate	$0.07	$0.07	$0.07
kWh req.	**59,386**	**113,350**	**207,829**

Table 16: Energy output requirements for different target REPs

Results of the EA2 scenarios are presented in figures 14, 15 (energy impacts for LR and SI scenarios), 16 and 17 (solid waste impacts for LR and SI scenarios). In the LR scenario the increase in energy consumption and solid waste generation from material placement and decommissioning is greatest for the low wind system. Energy burdens (increases from material placement and decommissioning) for the High Wind REP 20% system are actually 1/3 of energy burdens for the Low PV REP 5% system. The SI scenario has similar results only to a lesser degree. These results indicate the importance of strong site renewable resources, however corresponding savings in grid fossil energy consumption during operations dramatically overshadow differences in burdens. Under any given configuration the energy benefits are equal, and are many times the burdens (.4%-6% of energy savings in the LR and SI scenarios). Results are less dramatic for solid waste generation, in which the burdens are a more significant fraction of the savings (1-15% in the LR and SI scenarios).

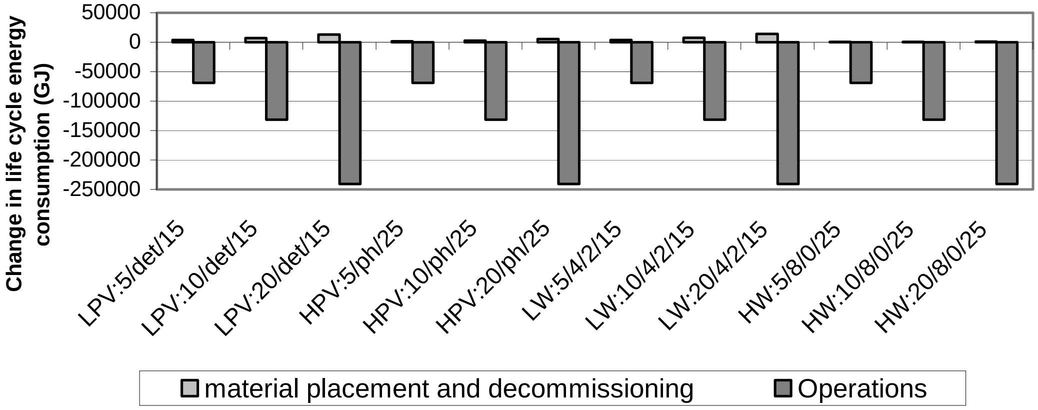

Figure 14: LR scenario life cycle energy changes[22]

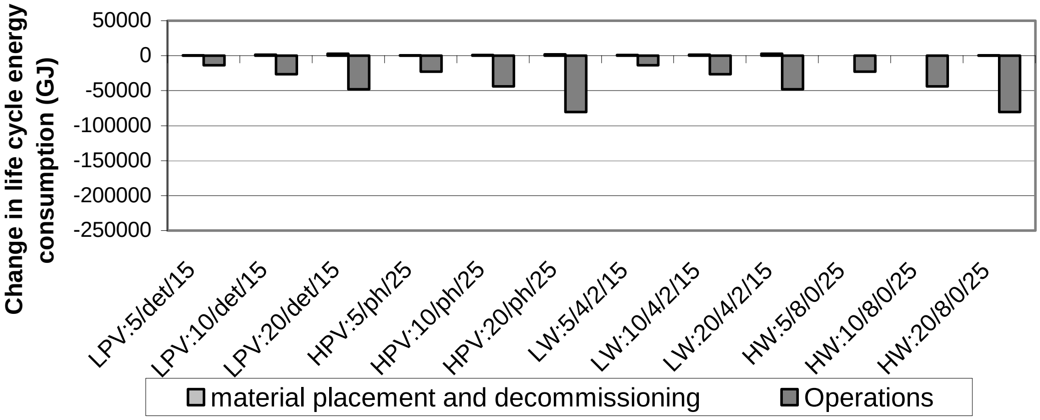

Figure 15: SI scenario life cycle energy changes

It is also clear from comparing figures 14 and 15, and comparing figures 16 and 17, that differences in impact between the SI and LR scenarios are directly proportional to the number of replacements over the building life span, i.e. both burdens and benefits increase proportionately.

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[22] Each scenario is coded as follows - System type: Target REP/ Renewable Variable 1/ 2/ 3/ System lifespan. Thus HW:20/8/0/25 would equal High wind: 20% target REP/ 8meters per second / 0 roughness/ 25 year life span.

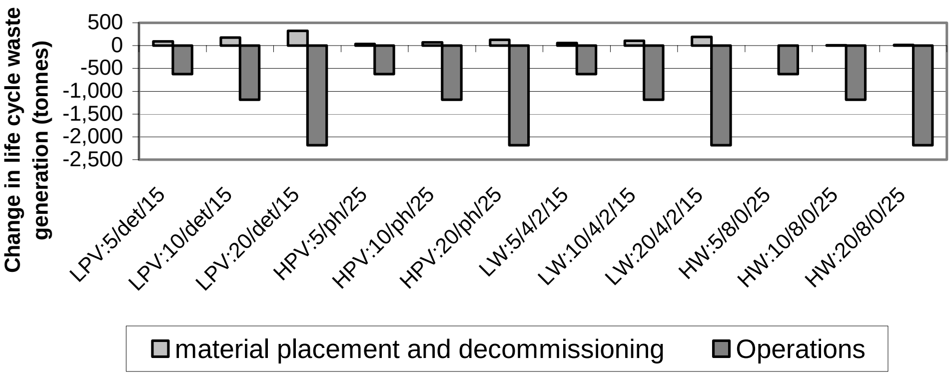

Figure 16: LR scenario life cycle waste changes

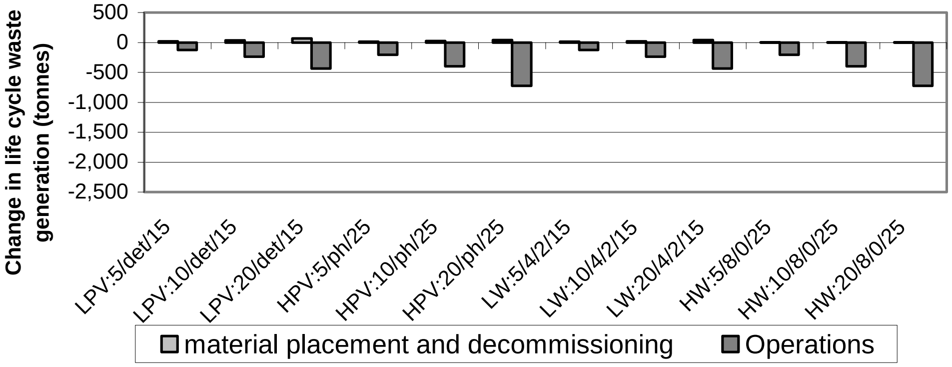

Figure 17: SI scenario life cycle waste changes

Figure 18 illustrates the cumulative impact of each renewable system. In terms of life cycle impacts SI scenario systems yielded .5-2.3% and 1.1-7.6% reductions in life cycle energy and solid waste generation respectively. The LR scenario systems yielded 2.6-9.6% and 5.6-22.9% reductions in life cycle energy and wastes respectively. While specifying a higher target REP in the SI scenario results in only modest environmental improvements over the lower target REP, for the LR scenario the difference in benefits between a 5% and 20% REP are much greater.

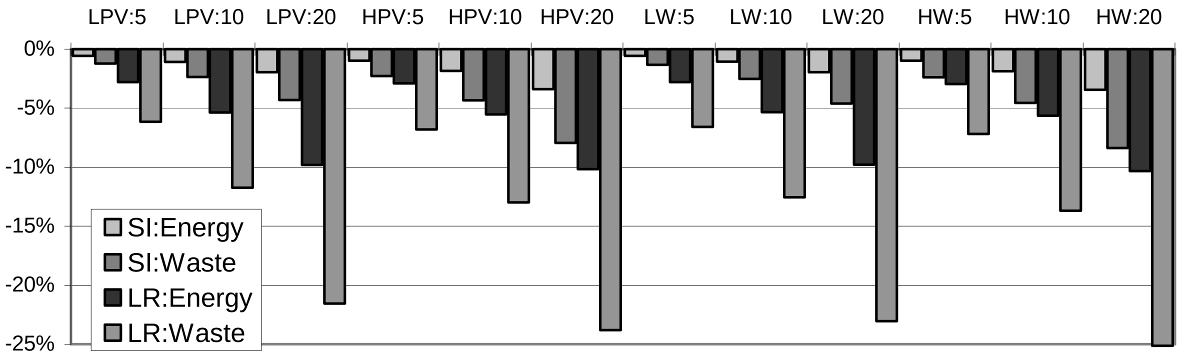

Figure 18: Change in life cycle burdens from SWH in SI and LR scenarios

EA2: Analysis

The range of effectiveness of renewable systems in buildings is dependent on the performance of the system. Given the expense of renewable systems it is ideal to consider EA2 in sites with strong renewable resources. However, based on these scenarios, the additional energy consumption and solid waste generation due to variations in site renewable resources, renewable system lifespan, and even the type of renewable system level out when considered against the much greater energy and solid waste savings from reduced grid energy consumption.

The inability of this credit to encourage the replacements of renewable systems over the building life span limits the potential benefits of this credit. While it is unrealistic for initial building owners to commit to future system replacements, it is clear from the preceding results that the greatest impacts of these systems are seen over extended periods of time.

Complications involved with the calculation procedures appear to artificially inflate the REP. It is somewhat misleading to the general public to state a building has met 20% of its energy consumption through renewable power, when the actual amount may be much less. Since a LEED certification is intended, in part, to be a marketing tool to enable lay people to evaluate the "greenness" of a building it is important that claims like 20% renewable power be as close as practical to what the lay person would commonly assume is meant. Experience with early ecolabeling programs teach that program credibility and long term comparability depends on the clarity of the individual credit claims[10].

EA2: Recommendations

Near Term

- Eliminate the double counting of REC in DEC″.
- Revisit the regional pricing structure in DEC. Normalize the DEC calculation to provide a comparable and equitable determination of REP so that buildings can be compared nationally.

Longer Term

- Specify replacement protocol, awarding more credit for commitment to replacement.

EA6: Green Power

EA6: Credit Intention

"Encourage the development and use of grid-source energy technologies on a net zero pollution basis [29] [p163]."

Not only does energy consumption in commercial buildings account for approximately 38% [1] [Table 2.1a] of the nation's energy consumption, primarily from nonrenewable fossil fuels, but also historically energy production accounts for three quarters of the greenhouse gas emissions in the U.S. [54]. Renewable energy production can be drastically cleaner than fossil energy production, and does not deplete limited fossil fuel reserves at anything approximating the rate of fossil energy production. While renewable energy production has increased dramatically over the past couple of decades renewable energy still only accounts for a small fraction of our national energy portfolio (11% of generated power including conventional hydropower, 2% without [1] [Table 8.1]. While onsite renewable energy production can be beneficial it is often not practical. The structure of our national grid makes renewable energy theoretically accessible to anyone. One of the major barriers to increased utility scale renewable energy production is the overwhelming market presence of the conventional energy industries. One response has been to create the Green-e certified renewable energy standard, a third party eco-label for renewable energy providers [68]. Recognizing that incentives can facilitate the emergence of markets for renewable source grid power, LEED has included a "green power" credit, which rewards the choice, where available, of renewable power as the grid based source.

EA6: Credit Structure

On the surface EA6 is one of the simplest credits in LEED 2.0; 1 point is available for engaging in a 2-year contract with a power provider who meets the Center for Resource Solutions Green-e requirements [68]. The process for fulfilling the EA6 requirements is to locate a certified energy provider, and sign on for 2 years of service. Currently the requirements for a Green-e certification are energy sources where,

- 50% or more of the electricity supply comes from one or more of these eligible renewable resources: solar electric, wind, geothermal, biomass[23], and small or certified low-impact hydro facilities,
- If a portion of the electricity is non-renewable, the air emissions are equal to or lower than those produced by conventional electricity,
- There are no specific purchases of nuclear power, and
- The product meets the Green-e new renewable requirement.[24]

Access to Green-e certified power generally requires a deregulated energy market where consumers can choose their own power provider and a regional power provider with renewable production facilities. Many states are in the process of deregulating their markets, however access is currently quite limited. The available mixes of power utilize most of the renewable energy systems in the Green-e certification to varying degrees (Table 17).

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[23] Apparently, from looking at different Green-e products, landfill methane capture is being treated as biomass by CRS.

[24] The Green-e Program's new renewable requirement defines new renewables as renewables that are generated from solar electric, wind, biomass and geothermal facilities which have come online since 1997, and in New England since 1998.

Energy Provider	**Grid**	**biomass**	**landfill methane**	**PV**	**wind**	**small hydropower**	**geothermal**
CT Energy Co-op	0%		27%		5%	68%	
GreenEnergy	0%	71%	29%				
GreenEnergy	0%	100%					
GreenEnergy	43%	51%		1%	1%	2%	2%
GreenMountain Energy	50%	45%		1%	4%		
GreenMountain Energy	0%				100%		
GreenSmart	0%						100%
GreenSmart	0%					50%	50%
The Mack Service Group	80%					20%	

Table 17: Sample Green-e power mixs

EA6: Credit Calculation Discussion

There are no special issues related to the EA6 credit calculation process.

EA6: Simulation: Key Parameters

The environmental impacts of renewable power sources are not all equivalent. For example, in the manufacture of each system there are different burdens associated with resource extraction and material production. The national grid is already a mix of fossil fuels, renewables and nuclear energy sources, each with its own performance variation depending on regional mix. As such, different combinations of grid and renewable energy sources will have different environmental impacts. An important measure of energy system environmental performance is the Fossil Energy Ratio (FER), which is the energy (generally electrical) output divided by the primary fossil energy input. For the North American Electric Reliability Council (NERC) regional grids this ratio ranges from .23 - .36 [55], which means that the system operates at a net loss of depletable energy resources. One approach for a minimum criteria for a "sustainable" energy system is an FER greater than 1 [69] because at that point energy production exceeds depletable energy resource consumption. The key parameters for this credit are –

- FERs of different renewable energy systems.
- FERs for the NERC regional grids.
- Mix composition of Green-e products.
- Number of contract years for Green-e power product

EA6: Simulation: Methods

There are several different studies of the life cycle environmental performance of different energy systems, each with slightly different methods and results. For the EA6 simulation it is more important to explore the impacts of a range of performances across different systems than to validate the results of specific studies (Table 18). Renewable energy system performance is entirely dependent on site resources, the specific technology utilized, and long term maintenance conditions. As such, the following are sample renewable systems utilized for the purpose of this simulation.

Energy System	**FER**	**Source**
Grid (NERC regions)	.23 - .36	[55]
Wind	37	[65], [66]
Small Hydro	23	[70]
Geothermal	18	[71]
Biomass	16	[72]
Photovoltaics	6	[73]
Landfill Methane	2	[55]

Table 18: Fossil Energy Ratios (FERs) for renewable energy systems

Based on the selected energy production FERs, a model is constructed that allows a specific mix of power to be set and the subsequent allocation of energy system burdens to be incorporated into the SWH model. For the EA6 simulation the annual load being met by the external electricity provider (30% of total for the SWH status quo) is multiplied by contract years and allocated between renewable and grid sources according to the selected mix percentages. The total renewable electricity output is divided by the Renewable FER (Equation 13) to determine primary fossil needs for the renewable portion and the result is added to the total operations phase primary energy demand. The grid portion is added to the total annual load multiplied by the non-contract years and input to the existing SWH grid dataset (the ECAR region DEAM dataset [55]).

$$Renewable\ FER = \frac{1}{\left[\left(\frac{\%\ renew_1}{renew_1\ FER}\right)+\ldots+\left(\frac{\%\ renew_n}{renew_n\ FER}\right)\right]}$$

Equation 13: Renewable FER

The net result of this method is that as the grid percentage of a mix decreases the total grid load decreases, primary energy demands and solid waste burdens from grid energy production decrease, while the renewable energy burdens increase.

This method only represents the environmental performance of renewable systems in terms of their fossil energy consumption, and does not capture other environmental impacts associated with these systems, including solid waste generation associated with system operation. In these simulations solid waste burdens are considered negligible relative to the substantial solid waste generation avoided through offset grid energy production. For example, a simple analysis of a 50% grid and 50% biomass mix for 75 years with .48g/kWh annual waste for biomass [72] has an increase of 8 tonnes for the biomass energy production wastes, yet yields a savings of 2300 tonnes from offset grid energy production. Other renewable systems are assumed to have less waste generation than the biomass system. The result of this approach is that for all the renewable systems the solid waste impacts only reflect solid waste generation avoided through offset grid production and are equivalent for all the renewable systems.

EA6: Simulation: Results

The first EA6 examination focuses on the effects of grid mix, contract years and FER in the current SWH building. The total status quo burdens for SWH are 2,300,000 GJ of primary energy and 8,600 tonnes of solid waste over the 75-year lifespan. Operations phase burdens account for over 95% of life cycle burdens, so reductions in this phase can dramatically reduce total life cycle burdens. The activities in this phase include water services, electricity produced in the UM CHP and the electricity purchased from the local utility. For SWH only 30% of electrical load is contracted out to a local energy provider; only this portion is being modeled in this example, and site electrical demand only accounts for 41% of total primary energy during operations.

Figure 19 compares the use of low, medium and high FER (1.9, 16 and 37 respectively) renewable sources in scenarios with a 50% grid mix and a 100% renewable mix over 2 years and 75 years.

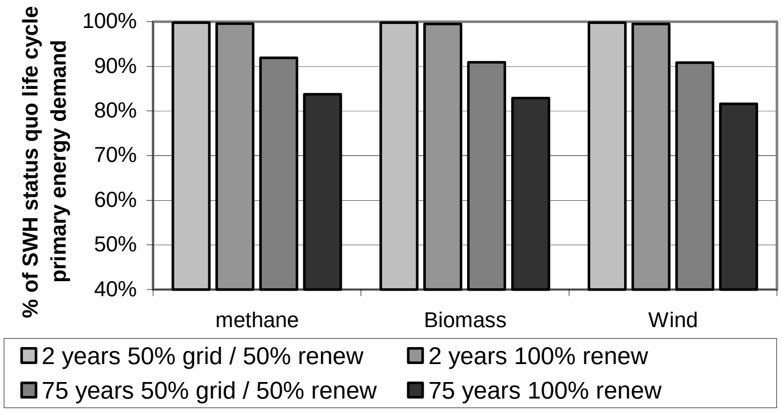

Figure 19: Mix, contract years and FER comparisons under current SWH energy service (30% of total electric load subject to EA6)

With a 2-year contract regardless of the mix of renewable energy, only a small reduction in total life cycle energy burdens occurs. However, over 75 years of renewable based electrical service both the 50% and 100% renewable mixes contribute to large energy reductions. Over this time frame the impacts of improved FER begin to stand out, although improvements in FER (1.9-37) still have less benefit than reductions in the percentage of regional grid power in the energy mix (50%-100%).

For a 2-year renewable service period the reduction in wastes is about 1% of total life cycle waste generation. For 75 years of renewable service the reduction in waste is 23-45% depending on grid contribution (as mentioned in the preceding section, waste reductions are equivalent regardless of renewable energy source). The greater amount of waste reduction versus energy reduction is due to the fact that utility electrical generation is responsible for a disproportionate amount of waste production. The relationship between grid contribution and FER is further explored in figure 20. While decreasing the grid contribution from the Green-e maximum of 50% to 0% can increase life cycle energy consumption savings between 8-18%; improving the FER from 2-37 only results in a 1-2% improvement in reductions, depending on the grid contribution.

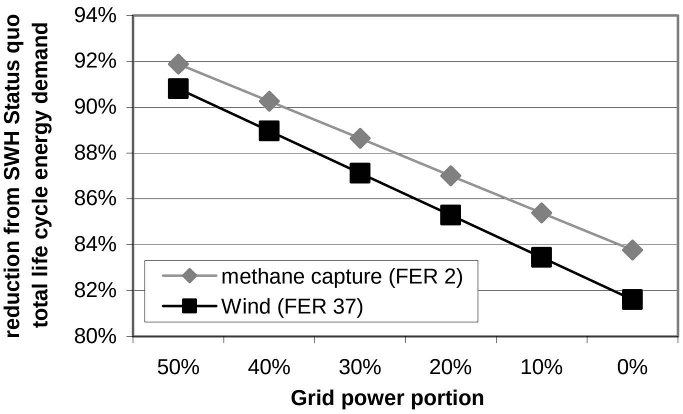

Figure 20: Changes in grid contribution for different FER renewable sources

Figure 21 is based on substituting only the portion of SWH's electrical load currently provided by the local utility. In the following scenario the Green-e provider supplies 100% of SWH's electrical load and for non-contract years the grid supplies the entire electrical load. This scenario increases overall energy consumption because the natural gas turbine data set used to model the UM portion of electrical load has a greater efficiency than the regional grid, therefore base case life cycle burdens for this scenario are 2,800,000 GJ and 17,300 tonnes of solid waste.

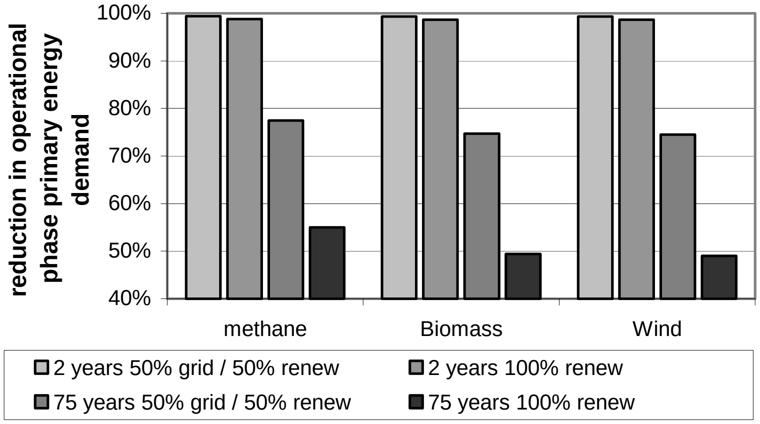

Figure 21: Mix, contract years and FER comparisons under total utility-based energy service (100% of total electric load subject to EA6)

Not surprisingly, greater reductions in burdens are available when the renewable energy provider is utilized for all electrical needs. While reductions for 2 years of renewable service are still small, over the whole building lifespan use of renewable energy sources achieves reductions of 25% to 50% of life cycle energy consumption depending on grid contribution. Waste reductions are similarly intensified over the preceding scenario (1-2% for 2 years and 38-75% for 75 years).

EA6 is intended to stimulate the use of energy sources that do not deplete fossil fuel resources. With this intention in mind it is interesting to assess under what conditions could the whole building have at least a lifespan FER of 1, where total fossil inputs are equal to total site energy demand. For every year of renewable service (where the whole energy mix has an FER greater than 1), fossil inputs are less than site energy consumption. For the years of grid-based power only, fossil inputs are greater than site consumption. In figure 22 each bar represents the years of renewable service with different percentages of grid power in the renewable service (FER>1) required to balance out the years of grid-based only service (FER<1). The number of years of 100% renewable service required to balance out the "debt" for the fossil burdens of the grid-only years is at best 57 out of 75 years, with a high FER renewable energy source. As the renewable service increases in grid percentage (up to 20%), the number of years of renewable service required to achieve a total system FER of 1 quickly rises, reaching a point where the renewable service must last for the entire building lifespan (or beyond, for low FER renewable sources) to balance the grid fossil inputs.

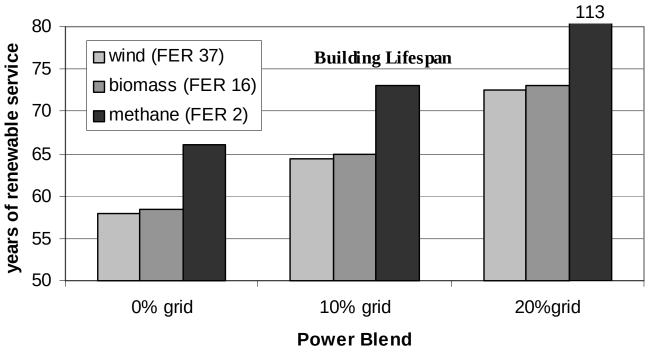

Figure 22: Total system balancing (FER=1) scenarios

Every regional power grid has a different mix of primarily fossil energy systems (coal, oil, natural gas) as well as some nuclear, hydropower and renewables. As demonstrated above, the grid FER impacts the overall energy system performance dramatically. In all the previous scenarios the local ECAR region grid efficiency of .23 has been used. However the ECAR region has one of the lowest FERs in the country, due to large amounts of older coal power plants. The WSCC region (see Appendix I for a map of the NERC regions of the U.S.), which comprises several western states, has a much higher FER, due in part to the large percentage of hydropower [55]. Figure 23 illustrates the percentage of low and high FER renewable energy in a power mix that would have to be utilized in different regions of the country to achieve a total system FER of 1. What this figure demonstrates is a broad range in performance differences between different regions. In this example, a Green-e product in the western U.S. with 70% wind / 30% grid mix is operating at a “gain” in terms of energy production versus depletable resource consumption, while the same system in the Midwest would be operating at a “loss”.

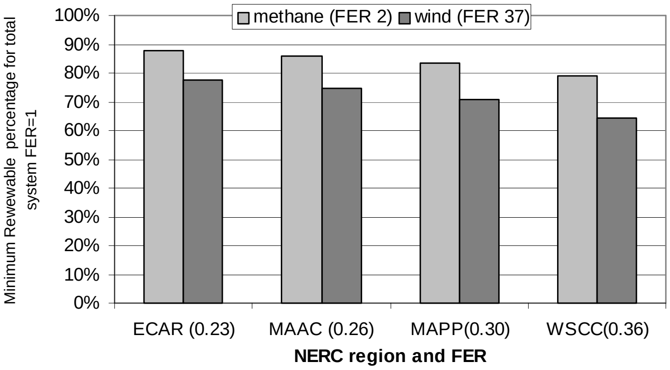

Figure 23: Comparison of different FERs from NERC regions

EA6: Analysis

The 2-year contract limitation and the provision in Green-e for grid contributions up to 50% severely limits the potential benefits of this credit. It may be hoped that building owners continue to contract with a renewable energy provider after the 2-year contract expires, but there is no guarantee. Obviously the market availability of individual Green-e mixes limits actual choice for EA6. Due to the currently limited market of renewable energy providers it is important to stimulate market demand for all kinds of renewable energy sources, so the Green-e program's grid mix may represent a pragmatic approach. However, it is also important to acknowledge the wide range of environmental effectiveness contained within the Green-e rating. Finally, variations in regional grid effectiveness mean that the benefits of this credit are not equivalently distributed across the U.S.

EA6: Recommendations

Near Term

- Expand available LEED credit points for longer contract periods.
- Review the CRS inclusion of grid-based power in Green-e products.

Longer Term

- Create a tiered credit tied to the total system performance. Such a tiered system could factor in renewable system FER, regional grid FER and contract years.

INTRACREDIT COMPARISONS

Per LEED point evaluation

This section compares results of the preceding simulations to each other. Ideally any given accumulation of LEED points should have an equivalent environmental "benefit". Obviously there is no easy way to compare the benefits of the diverse categories of the LEED rating system. On what basis can energy savings, water use reductions or air quality improvements be normalized? However, specific impacts across different credits should not provide grossly different results. Further, benefits from achieving successively higher credit tiers should have some rational relationship to each other (i.e. increased environmental performance, increased costs or technical challenges). Equivalence is important for a rating program to ensure long-term validity and standardization. Users of the program should feel confident that any given choice that accumulates points is improving the environmental performance of their building equally so that buildings of dissimilar impacts do not hold equivalent ratings.

For this intracredit comparison, best and worst case environmental performance scenarios for each credit tier are normalized to MJ and tonnes saved per LEED point over the SWH status quo. As previously stated there are other goals of individual LEED credits than energy conservation or solid waste avoidance, which this study does not evaluate. However, it is still useful to compare individual credits based on these two impacts as a starting point to the discussion of LEED intracredit comparability.

Results

Figures 24 and 25 illustrate the results of the intracredit comparisons (see Appendix J for a table of scenario coding definitions). Results for individual credit scenarios cluster around each other, both with respect to the best/worst cases and across credit tiers, suggesting that internally they are relatively consistent. For example, the four EA2 scenarios (LowPV to High Wind across the 5% to 20% REP credit tiers) only range from a decrease of 13,000-26,000 GJ per point. Changes in building lifespan primary energy consumption from the SWH status quo varied from an increase of 30,000 GJ (EA1/25%elec) to a savings of almost 300,000 GJ per LEED point

(EA1/100% gas). These results do not portray a balanced allocation of credits. Fulfilling credit requirements does not necessarily yield an improvement over the SWH status quo (EA1/25%elec, MR5/HMLC/LM500RM500, MR5HMLC/LM500). MR5 and MR2 have quite limited benefits relative to other credits. MR5's potential increase over the SWH status quo (27,000 GJ) far exceeds its potential decrease (400 GJ). As expected, the *Energy and Atmosphere* credits as a group offer substantially more energy savings per LEED point than the *Materials and Resources* credits.

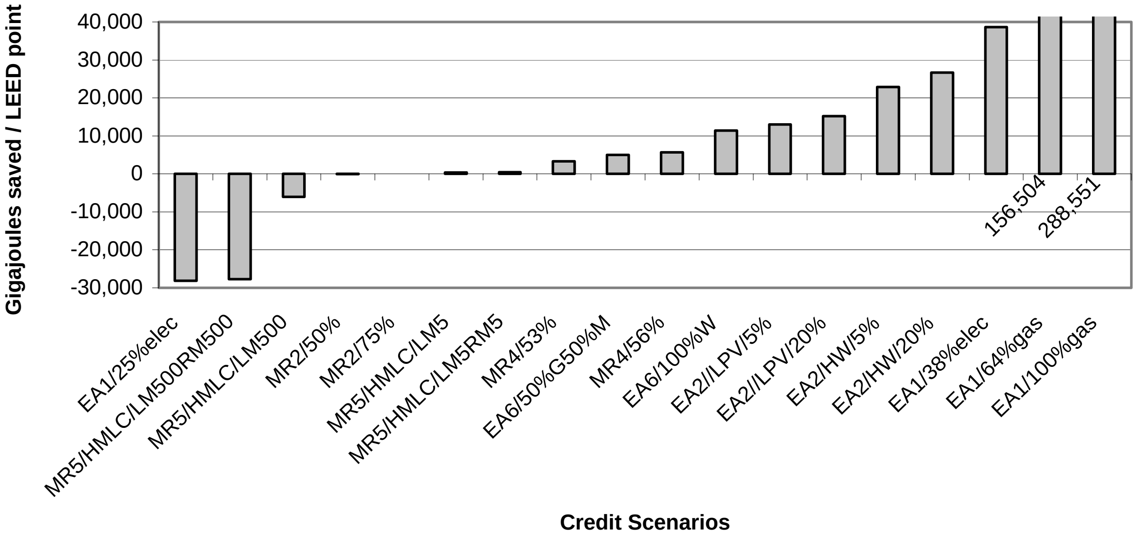

Figure 24: Intracredit comparison of energy performance

EA1, which has results at both ends of the scale, is a notable exception to the clustering trend in other credits. The large increase in lifespan energy consumption in the EA1 scenario (EA1/25%elec) represents a 25% reduction in electric consumption over ASHRAE minimums, not a reduction from the SWH status quo. The range of outcomes among EA1 scenarios is primarily due to the EA1 calculation methods discussed previously.

These scenarios go from an increase of 1% (EA1/25%elec) to a reduction of 12% (EA1/100%gas) of total life cycle primary energy burdens. However, setting aside the extreme cases of EA1, none of the remaining scenarios individually amount to a change of more than 1% of total building life cycle primary energy burdens.

The intracredit comparison of solid waste generation also reveals a wide range of outcomes. For solid waste generation an EA1 scenario (EA1/38%gas) accounts for the largest per point decrease due to reductions in solid waste generation from grid electric production. Individual credit scenarios for solid waste generation also cluster. Similar to the energy results the least effective credit in this comparison is MR5.

The solid waste impacts of these scenarios go from a 2% (200 tonnes) increase to a 7% (600 tonnes) reduction in total life cycle solid waste generation (including EA1 this time). Interestingly, given the emphasis on solid waste reduction in the *Materials and Resources* credits, the *Energy and Atmosphere* credits as a group also offer more opportunity for solid waste reduction per point than the *Materials and Resources* credits.

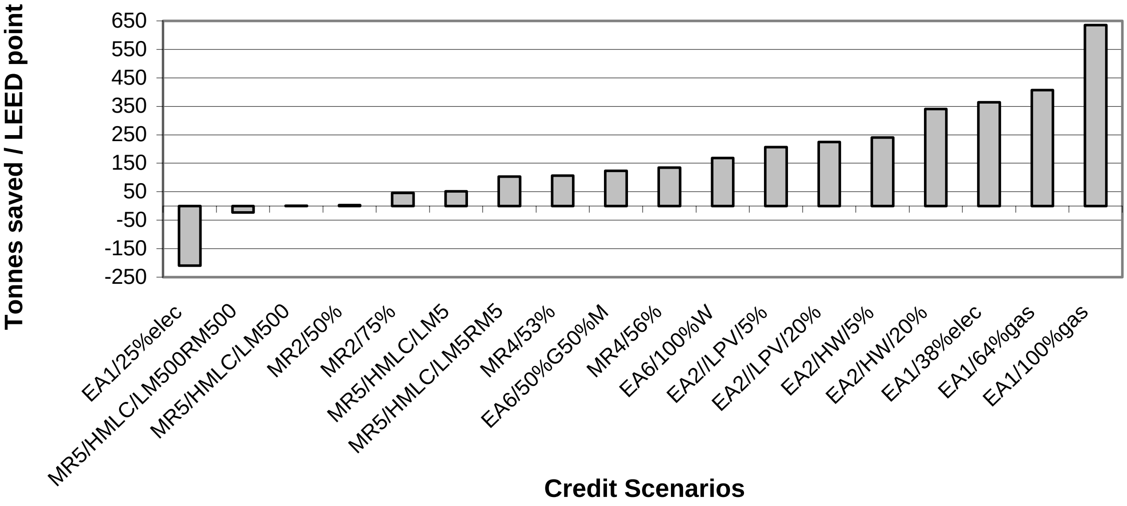

Figure 25: Intracredit comparison of solid waste impacts

Each of the preceding scenarios is structured to just meet the requirements for achieving LEED credits. In many cases there are opportunities to exceed these requirements. It is interesting to consider the possible additional environmental benefits for surpassing LEED requirements. Some further examples are presented that explore outcomes from exceeding the minimum requirements for a given credit tier (Figure 26). The two scenarios are an MR4 (Recycled Materials) 75% RCV and an EA6 building lifespan use of wind power. Results range from .3 – 18% reduction in life span energy consumption and 9% – 45% reduction in life span solid waste generation per point. EA6, with a 100% wind source utilized for the entire building lifespan (which only accounts for 1 possible LEED point), has potentially great benefits for a credit that requires no upfront costs, change in construction practices or adoption of new building technologies. The MR4 scenario with a 75% RCV offers little additional benefit (6,000 GJ, 700 tonnes) than the two previous MR2 examples (at best 5600 GJ, 400 tonnes).

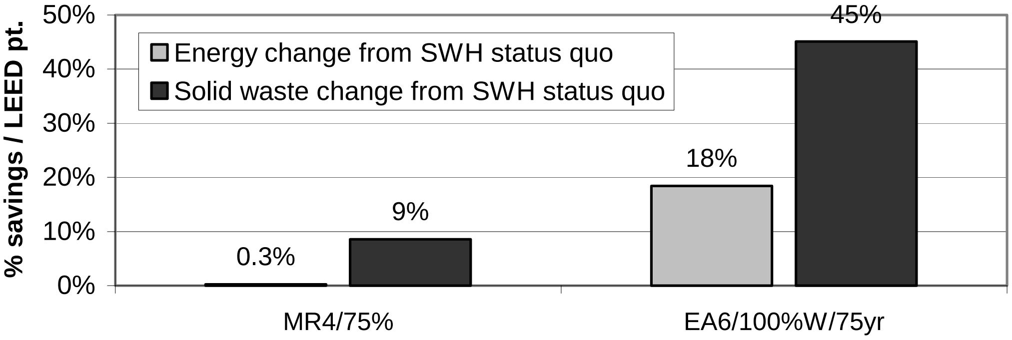

Figure 26: Intracredit comparison of energy and solid waste impacts from exceeding LEED minimums

The results of the scenarios for exceeding LEED minimum requirements also raise some issues about the LEED innovation credit (ID1). ID1 allows up to 3 points for "exceptional performance above requirements"[29][p273]. Exceptional performance is credited by documenting that a project has significantly exceeded existing credit thresholds. In this case study, while there is a relationship in EA6 between exceeding the requirements and increased environmental benefits, for MR4 there does not appear to be.

Analysis

While in absolute terms these credits span a wide range of outcomes, from a total lifespan perspective the diversity of outcomes between credits appears more moderate. Given the many bounding variables that define this project that are subject to circumstances or available data, this is an encouraging outcome. While some of the outlying scenarios (MR5, EA1) indicate more problematic disparities, overall this intracredit comparison of energy and solid waste impacts suggests that with refinement the benefits of individual credits may be more closely aligned.

Defining an acceptable range between credits is not an easy task. Some might argue that the energy results (all about 1% of life cycle total) are already very consistent. However, consider the cumulative effect of “minor” differences through many credits: depending on which points are chosen, two buildings, one with a hypothetical Silver rating, the other Gold (but only by a few points) could actually be “equivalent” environmentally, yet in terms of the LEED rating program the higher rated building can claim greater status and accomplishment. The goal of LEED is not to create buildings whose actual environmental performance contradicts their ratings to such a degree that the non-environmental benefits of a LEED certification (marketing, status, etc.) do not match the environmental benefits.

Regarding the negative impacts in some of the scenarios, it should be remembered that these results are based on change from the SWH status quo, and as such an increase in energy consumption or solid waste generation is not an absolute negative result. However, these results do suggest that some LEED credit methods may not guide a building design towards improved environmental impacts over current industry practices.

The scenarios for exceeding LEED minimum requirements suggest two points. First, if there is significant room for exceeding the requirements of an individual credit (e.g., EA6), perhaps the credit mechanism should be reviewed to allocate more points and conversely, if the range of benefits for a given credit is too small (e.g., MR4), then that credit’s allotment also warrants review. Second, it is crucial if a process (e.g., ID1) is in place to allow additional credit for exceeding thresholds, that the calculation methods not be internally flawed, and that there is a relationship between the calculated credit value (e.g., MR4 RCV, EA1 ESP) and the environmental benefit.

Finally, the results of these scenarios highlight the need for a total performance approach in LEED rather than a portfolio of credit achievements. For example, the environmental benefits of life span adoption of EA6 might conceivably accomplish as much or more than implementation of several other credits needed to accomplish a LEED rating. Disparities such as those in this report are removed when standards are based on lifespan performance. Further, opportunities are created to achieve performance goals in unique ways that may be overlooked in the current system. While methods are not currently available for evaluating all the desired benefits in a sufficiently quantitative way as to be truly balanced [8], it is clear from these results that such an approach should be the goal, and in the interim methods should be refined to more closely approximate that goal.

Recommendations

Near Term

- Evaluate the relative "benefits" of EA1, MR4 and MR5 to ensure that their credit value is appropriate to their environmental contribution.
- Expand and refine EA6 and EA1 to balance and encompass their potential contributions.

Longer Term

- Develop refined metrics of individual credit environmental benefits to permit transparent quantitative comparability.

CONCLUSIONS

Research Conclusions

Conclusions about the specific results of this research project are grouped into several categories. Each of these categories describes an effect that contributes to a disparity of outcome, either within the individual credit internally or in the intracredit comparison. Many of the results of individual credit simulations are influenced by several of these categories.

Calculation Methods

Throughout these simulations the LEED credit calculation processes contribute to disparities of outcome. In many cases the economic basis of the calculations directly led to results in which the specific measured environmental impacts did not align with the LEED rating method. The MR4 Recycled Content Value (RCV), the MR5 Manufacturing Rate (MR) and Extraction Rate (ER), and the EA2 Renewable Energy Contribution (REC), are prime examples of calculation methods with economic calculation issues. Two factors, variations in material or energy pricing and a lack of relationship between costs and environmental impact, lead to problematic results when calculation methods are economically based.

Other calculation issues are more strictly formula related, such as the double counting of EA2's Renewable Energy Contribution (REC) in the Design Energy Cost (DEC″) calculation or the nesting of MR5's ER into MR. In those cases the calculation method itself creates a disparity of outcome between the calculated value and the measured environmental impacts.

While this project did not assess policy or practical reasons for the structure of individual credit calculation methods, the lack of relationship in several cases between environmental impact and the LEED calculated value are noteworthy and introduce conflicts between the credit intention and the outcome.

Threshold Appropriateness

In several cases results of this analysis raise questions about the appropriateness of the thresholds utilized for individual credits. Thresholds include credit tier thresholds such as the REP in MR2, or an internal threshold such as the post-industrial and post-consumer thresholds in MR4. In some cases the threshold may be too low to represent a significant enough advance, and the credit may be achieved for activities that are too close to industry norms to represent a "green" approach (MR4). In other cases thresholds may be so low or so high as to create credits with limited benefits (MR2) or an abundance of benefits (EA1) in relation to other credits. These threshold issues all reflect the need to "calibrate" the scales used in LEED. Determining the appropriate scale and measure is not an easy task, but it is necessary in order to ensure that LEED credits fulfill their intentions.

Comparability

An important goal of LEED is to provide a standard of measure, so that buildings with LEED ratings are comparable. One assumes this to mean that nationally, buildings of similar ratings are environmentally equivalent. However, results of this project indicate that regionally variable inputs such as energy pricing can directly influence the requirements of individual credits so that, depending on region, buildings with similar ratings could have different requirements. For example, in EA2 the renewable energy system size needed to meet a target REP that is in part dependent on regional energy pricing, with the result that a building in a region with high energy prices needs a smaller system than a building in a region with lower energy prices (assuming the renewable resources are equal). While both buildings can claim equivalent LEED REP (the public measure), the building with the lower energy pricing will actually be producing more renewable energy. While regionalism is perhaps a necessary element in LEED (see the discussion of Environmental Performance Assessment below), the lack of clear integration currently undermines the actual comparability of LEED rated buildings.

Distinctions in Applied Solutions

LEED was designed to provide a simple-to-use approach to rating buildings. However in this project there are many cases where the simplicity creates a lack of distinction in application. For example, the MR4 RCV single recycled percentage threshold is not responsive to actual material recycled content, such that structural steel, which represents no improvement over industry norms, can overwhelm the calculation, while flyash concrete, which represents a significant advance over industry practice, is devalued, all due to a flat recycled content measure. Incorporation of LEED into a building project may stimulate the consideration of energy or resource conserving techniques and systems, but the user of LEED still has to make decisions at the individual material and equipment level. At this level all choices that fulfill LEED criteria are not equally beneficial. It is important that LEED credit mechanisms account for variables of the specific conditions that are invoked by individual credits.

General Research Conclusion

This project revealed a variety of discrepancies in outcome in LEED credits. These discrepancies undermine the achievement of individual credit intentions and the goals of the program as a whole. Life Cycle Assessment has proven to be a valuable methodology for simulation of impacts from utilization of the LEED program. The lack of comparability between LEED ratings and LCA results indicates that when considered in a life cycle perspective LEED does not provide a consistent, organized structure for achievement of environmental goals. Further, the disaggregation into individual credits may stimulate specific solutions, but overall building integration may be less than ideal. Finally the lack of balanced results may lead to so much variation in total building environmental performance that a building's rating may not align with its actual performance. In these respects the LEED program does not fulfill its goal of providing a standard of measure. While LEED appears to be accomplishing the goals of an eco-labeling program that is as a marketing and policy tool it is not as successful at being a comprehensive methodology for assessment of environmental impacts. This is especially troubling from a consumer perspective, as the LEED rating is intended to become the "currency" of environmental value, upon which future users, owners, and public agencies rely. Refinement of LEED should emphasize integration of life cycle oriented measures and standards.

Future work

Expanded Assessment Categories

The single most important avenue for future work would be expanding the impact assessment categories used for measurement. Repeatedly this report has balanced critiques of LEED within the context of the limited measures employed. Future work could expand on the energy and solid waste assessment to include assessments such as water consumption, global warming potential, ecotoxicity, human toxicity, acidification, resource depletion and land use. These measures were unavailable because of limitations in project scope, limitations in current data sources and complications in current assessment techniques. Some of these may be addressed in the near term, others may not be accomplished without further developments in assessment methods, but an assessment of LEED remains incomplete until a more comprehensive assessment of other impacts areas can be conducted.

Expanded Credit Simulation

In addition to expanding assessment measures, future work would greatly benefit from expanding the number of individual credits simulated. LEED certification requires a minimum of 29 credit points, this report at most can account for 20 points. Limitations in current assessment techniques prevent an assessment of some individual credits where the environmental benefits are less quantifiable (brownfield redevelopment) or less comparable to other benefits (low-emitting materials). However as the program matures it will become increasingly important to provide a valid basis for all credit allotments.

Expanded Building Forms

This report is based on a single case study building. In order to further assess the impacts of LEED it is important to undertake such an analysis for a range of building types and sizes. One feature of LEED that this report does not address is the scalability of ratings. Currently LEED ratings are not distinguished based on the size of a building. However, the impact differences from conservation of energy, between a 10,000 m^2 and a 100,000 m^2 building for example, can be large. Further, the effects of climate region, structural forms, construction techniques and other factors may further disrupt the life cycle impacts of LEED credits in as yet unknown ways.

Refinement of Data Sources and Modeling

In the future refinement of modeling techniques and data sources could enhance an assessment of this kind. A more developed thermal model would have provided more accuracy to this report as well as enabled more detailed modeling of specific feature changes. Further, the original SWH LCI is based primarily on DEAM datasets [55], which often represent the best available source, but are not necessarily representative of the specific material or processes being modeled. Additionally, many of the longer term recommendations in this report hinge on the availability of comprehensive data on material and system properties, and industry practices and potential. As of yet most of this data is not yet available. Future work could target these gaps in an effort to provide validation for LEED metrics and methods.

LEED Future Directions

This report is based on an analysis of LEED in a static context. This report documents potential effects of credit implementation from LEED, 2.0. But LEED is changing, specifically it is responding to feedback from the experience of its users. LEED is reshaping itself to better meet the needs of its customers. This report is, in part, intended to provide feedback about the potential environmental impacts of LEED implementation. It is hoped that it will contribute to the evolution of LEED by adding to the body of responses to the program. But there are other factors in the development of LEED: policy issues, implementation issues and evolving knowledge about the requirements and role for building environmental assessments which may drive the evolution of LEED to greater or lesser degrees than environmental priorities.

Credit Trend Analysis

While it is interesting to consider the environmental impacts from individual credits, there may be practical reasons why credits are more or less well utilized. It is important when discussing the impacts of LEED to consider not only the specific characteristics of individual credits but their usefulness in practice as well. LEED was designed to address whole building environmental performance, with an abundance of credits in each impact area. However, users of the program may, for a variety of reasons (such as cost, technical or political), utilize a more limited set. This analysis looks at data on credit choices to examine trends in credit selection. As of yet very few buildings have completed the LEED certification process, so this is a preliminary analysis based on limited data (35 cases)

Table 19 present statistics from available sources [74], [51] of the percentages of each impact area’s total credits that are being selected in projects. Of note is that in all cases the SS and IEQ impact areas are the most frequently utilized, while the MR and EA credits are consistently less often utilized.

	9 Portland Proposals	19 LEED registered Projects	7 LEED certified projects	average
Sustainable Sites	75%	58%	57%	**63%**
Water Efficiency	60%	56%	60%	**59%**
Energy & Atmosphere	*49%*	*36%*	*41%*	***42%***
Materials & Resources	*58%*	*37%*	*46%*	***47%***
Indoor Environmental Quality	74%	76%	60%	**70%**
Innovation & Design Process	38%	63%	80%	**60%**

Table 19: Percentages of total impact area credits selected

There is some indication that the high utilization of the IEQ credits is due in part to a sense of high importance among LEED users [51], and that some credits in the MR and EA sections are too expensive or difficult to document. If, as suggested, certain environmental benefits are perceived as more critical than others to the exclusion of certain credits, over time the comprehensive goals of LEED may falter as LEED credit choices begin to reflect general consensus on environmental priorities rather than a balanced approach. This may not be a negative outcome, since it is important that buildings reflect the environmental priorities of the surrounding society. However, if the general consensus is informed by limited knowledge, or knowledge that is at odds with actual environmental impacts, the shifting balance may be less desirable. Additionally, if credits are not being utilized because they are too complicated or expensive, then the credit structures may need to be reviewed. It is almost certain that users of LEED are going to engage in strategic planning for completion of certification requirements. The user of LEED is focused on achieving the desired total rating for the least cost and complication. The natural assumption is that all points are equal environmentally, so the realm of decision is limited to the practical constraints of credit use. Therefore certain credits, while perhaps desirable environmentally, if onerous to accomplish will be shunned in favor of more easily accessible credits.

A further examination of these results is provided through an analysis of the Portland data source (Table 20), which also included from each project an indication of *certain* credit use and *possible* credit use. This allows the creation of a simplified confidence rating for the credit areas. The confidence rating is a ratio of the percent *certain* to the percent *possible*. Similarly to the raw use percentages, the MR and EA credit areas scored the lowest, with the IEQ and SS credits scoring much higher. This result may reflect several factors; familiarity with requirements, understanding of the credit impacts or sense of importance attached to credits. Whatever the reason, this result is further indication that there may be long term impact area utilization issues due to factors such as program structure or user knowledge

9 Portland Projects	**certain**	**possible**	**certain/possible (confidence ratio)**
Sustainable Sites	58%	17%	3.5
Water Efficiency	33%	27%	1.3
Energy & Atmosphere	*26%*	*23%*	*1.1*
Materials & Resources	*35%*	*23%*	*1.5*
Indoor Environmental Quality	59%	15%	4.0
Innovation & Design Process	13%	24%	0.5

Table 20: Confidence rating for impact areas, from Acker [74]

Table 21 illustrates the specific credit choices for the MR and EA credits simulated in this report. Not surprisingly, there is a natural progression among all the tiered credit levels, most apparent with EA1, that lower tiers are more frequently utilized than the successive tiers. Due to the high upfront costs, EA2 is understandably the least utilized credit. MR2 and MR5, which were determined in this report to have very limited environmental benefits, are very well utilized.

Energy and Atmosphere Credits	**9**	**19**	**7**	**average**
1.1 Energy Optimization	100%	95%		**98%**
1.2 Energy Optimization	89%	47%		**68%**
1.3 Energy Optimization	22%	21%		**22%**
1.4 Energy Optimization	22%	11%		**17%**
2.1 Renewable Power	11%	32%		**22%**
2.2 Renewable Power	22%	26%		**24%**
2.3 Renewable Power	11%	16%		**14%**
6.0 Green Power	100%	26%		**63%**
Materials Credits	**9**	**19**	**7**	**average**
2.1 Construction Waste Management	100%	89%	71%	**87%**
2.2 Construction Waste Management	100%	42%	43%	**62%**
4.1 Recycled Materials	100%	74%	100%	**91%**
4.2 Recycled Materials	67%	21%	57%	**48%**
5.1 Local/Regional Materials	100%	95%	100%	**98%**
5.2 Local/Regional Materials	56%	26%	86%	**56%**

Table 21: Actual use of credits simulated in this report

While of limited scope (only 35 cases), this analysis does support the hypothesis that there are factors in LEED implementation that may lead to long-term credit utilization issues. The trend towards limited utilization of the MR and EA credits definitely highlights the need for an expanded assessment of LEED that can embrace all the impact areas, especially SS and IEQ.

Impending Program Development

LEED is a new program and one that is experiencing rapid proliferation. It is also a program undergoing rapid development. The evolution from LEED 1.0 to 2.0 was a significant improvement. As this report is being finalized LEED 2.1 has been released (August, 2002). A major emphasis of the LEED 2.1 revision is a streamlining of the documentation requirements, a step which may have little impact on the credit structures themselves, but which could also create further disparities in comparability depending on the boundaries of requirements. Major refinements are being withheld for the release of LEED 3.0, due in 2005. There has been some discussion that separation of LEED programs between application platforms (e.g., Interiors, Existing Buildings, Residential) may be revisited. The city of Portland has just released their own version of LEED, customized to their region and with specific additional features they felt were critical to the program, a custom approach to LEED that may be repeated as other city or state governments adopt LEED. All of these factors indicate a program in extreme flux. It is unclear what LEED will transform into over the next few years, but there is little doubt it will have a central role in the growth of green building development throughout the U.S.. This situation raises questions about the role of a building rating that is constantly changing, but for which the rated product of that rating, a building, has a lifetime of many decades. What will a 2002 LEED 2.0 Platinum rating mean in 2050? How will it compare to a LEED 10.0 Platinum rating then? While it is critical for LEED to stay current in terms of technologies and standards, it is also critical that the rating system have durability. Should a LEED rating be reassessed every 5 years according to current standards? Will there be an accumulation of resentment among LEED users, similar to the resentment over upgrades in the software world, over continual upgrades and changes? Will there be backlash because building owners want to capitalize on the investment in certification, but current standards may make an earlier rating meaningless? These are important questions far outside the sphere of this report to adequately address, but questions that need to be considered as the program moves into position as the "de facto green building standard" in the United States.

Next Generation Methodology: Environmental Performance Assessment (EPA)

The national success of LEED represents a historic milestone on the road towards improved environmental performance in the built environment. For the first time in this country a single program is bringing the diverse issues related to building environmental performance under one umbrella and attempting to standardize their implementation. But LEED is far from the evenhanded standard it is intended to be. As documented in the preceding simulations, many of the LEED credits operate independently of each other and don't necessarily relate equally.

Standards in building design are often about facilitating decision-making. For example, NFRC window ratings allow an architect to concentrate on the level of desired r-value or light transmission, ignoring the complexities that led to those standards. The level of decision making in LEED encourages consideration of environmental impacts at the level of individual credit options. However, this case study emphasizes that important environmental decisions are still made on the level of individual variables within each credit. If NFRC[25] ratings were insufficient to determine heat gain or light transmission, architects would be at a loss to specify windows and would have to divert attention and resources away from design of the whole building to resolve

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[25] National Fenestration Rating Council

individual window applications. Similarly, if LEED proves an insufficient standard for environmental impacts its value as a tool for environmental decision-making may be compromised.

Environmental Performance Assessment (EPA) is a new approach developed specifically for building assessment and intended as a comprehensive approach to integrate the strengths and bridge the inadequacies of ecolabeling and LCA. EPA is conceptually well developed, but has yet to be applied. The premier example of EPA is the Green Building Assessment Method (GBA). What differentiates EPA from LCA or ecolabeling is its integrated structure and attention to the balancing of application and resolution [14]. EPA grew out of experiences with other programs such as BEPAC, LEED and BREEAM.

> They [GBA] have built on the limitations of existing methods, and confronted areas of building performance assessment that were previously either ignored or poorly defined. By making rationales for structure, choice of performance issues and criteria descriptions explicit throughout the process, it has been possible to stimulate critical debate regarding the scope and role of building environmental performance assessment."[75].

Participants in the Green Building Challenge (1998, 2000) recognized limitations to existing programs and collectively defined characteristics of a next generation assessment method that would be comprehensive yet consistent, have market value and meet the needs of regional participants. [76], [8], [14], [77], [15]. While by no means a complete method, or one without conflicts, EPA does have a well-articulated set of principles, goals and methodological approaches. The following list is a description of EPA principles from Cole [75].

- Ensure consistency and rigor in terminology.
- Establish a scoring system that accepts both hard and soft data in a similar format.
- Include a weighting system that has defaults but is user-modifiable.
- Implement the system in a software system that will facilitate the work of making regional modifications, and that will also simplify the task of inputting building data and assessing candidate buildings.
- Design a system that can be modified to suit variations in national, regional and building type characteristics.
- Focus on relativistic assessments, by relating assessments to benchmarks that are based on applicable regulations or industry norms in each of the participating regions.

- Establish a structure that can be used at various levels of detail, from broad-brush assessments to detailed ones.
- Ensure consistency between levels of assessment, to the point where subcriteria form the complete and logical subsets of the criteria under which they are nested.

This articulation of EPA principles and requirements addresses many of the issues about LEED raised in this report. The use of relativistic assessments based on industry norms, regional weighting but international standards, and assessment level consistency all would strengthen LEED. While LEED has demonstrated that there is a desire and a market for a green building standard, and while the democratic process that led to its development may be attractive to industry participants, the program's lack of methodological consistency may undermine its long-term evolution and limit its effectiveness.

While LEED may have accomplished more in terms of a national rating program than any other previous tool, in order to become an established standard in the building process that practitioners can rely on, it is critical that it move towards greater consistency, clarity and transparency. EPA provides a compelling roadmap for the evolution of LEED. However, use of this roadmap requires an abundance of research such as the development of national databases of material and system environmental impacts, the definition of more comprehensive metrics based on total life cycle principles and industry partnership to establish baselines of practice from which LEED can structure performance improvement targets. This data is not going to emerge overnight. LCA based efforts such as the Building for Environmental and Economic Sustainability (BEES) database [26] are an important step in the right direction, developing the infrastructure that allows comparative assessments to be made, but much more work is needed. This work will require an as yet unrealized level of partnership among industry, government and third party organizations like the USGBC to develop the knowledge and tools to support assessments of this kind. LEED has provided an important cornerstone to this effort, defining much of the green building arena and engaging a wide array of stakeholders, but LEED alone does not provide an environmental assessment tool that the building industry can rely on. For that, a much greater effort must be expended by many stakeholders in the built environment.

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APPENDICES

Appendix A:
LEED 2.0 Credit List

Certified 26 to 32 points **Silver** 33 to 38 points **Gold** 39 to 51 points **Platinum** 52 or more points

Sustainable Sites		14
Prerequisite	**Erosion and Sedimentation Control**	x
Credit 1	**Site Selection**	1
Credit 2	**Urban Redevelopment**	1
Credit 3	**Brownfield Redevelopment**	1
Credit 4.1	**Alternative Transportation**, Public Transportation Access	1
Credit 4.2	**Alternative Transportation**, Bicycle Storage & Changing Rooms	1
Credit 4.3	**Alternative Transportation**, Alternative Fuel Refueling Stations	1
Credit 4.4	**Alternative Transportation**, Parking Capacity	1
Credit 5.1	**Reduced Site Disturbance**, Protect or Restore Open Space	1
Credit 5.2	**Reduced Site Disturbance**, Development Footprint	1
Credit 6.1	**Stormwater Management**, Rate and Quantity	1
Credit 6.2	**Stormwater Management**, Treatment	1
Credit 7.1	**Landscape & Exterior Design to Reduce Heat Islands**, Non-Roof	1
Credit 7.2	**Landscape & Exterior Design to Reduce Heat Islands**, Roof	1
Credit 8	**Light Pollution Reduction**	1

Water Efficiency		5
Credit 1.1	**Water Efficient Landscaping**, Reduce by 50%	1
Credit 1.2	**Water Efficient Landscaping**, No Potable Use or No Irrigation	1
Credit 2	**Innovative Wastewater Technologies**	1
Credit 3.1	**Water Use Reduction**, 20% Reduction	1
Credit 3.2	**Water Use Reduction**, 30% Reduction	1

Energy & Atmosphere		17
Prerequisite	**Fundamental Building Systems Commissioning**	x
Prerequisite	**Minimum Energy Performance**	x
Prerequisite	**CFC Reduction in HVAC&R Equipment**	x
Credit 1.1	**Optimize Energy Performance**, 20% New / 10% Existing	2
Credit 1.2	**Optimize Energy Performance**, 30% New / 20% Existing	2
Credit 1.3	**Optimize Energy Performance**, 40% New / 30% Existing	2
Credit 1.4	**Optimize Energy Performance**, 50% New / 40% Existing	2
Credit 1.5	**Optimize Energy Performance**, 60% New / 50% Existing	2
Credit 2.1	**Renewable Energy**, 5%	1
Credit 2.2	**Renewable Energy**, 10%	1
Credit 2.3	**Renewable Energy**, 20%	1
Credit 3	**Additional Commissioning**	1
Credit 4	**Ozone Depletion**	1
Credit 5	**Measurement & Verification**	1
Credit 6	**Green Power**	1

Materials & Resources		13
Prerequisite	**Storage & Collection of Recyclables**	x
Credit 1.1	**Building Reuse**, Maintain 75% of Existing Shell	1
Credit 1.2	**Building Reuse**, Maintain 100% of Existing Shell	1
Credit 1.3	**Building Reuse**, Maintain 100% Shell & 50% Non-Shell	1
Credit 2.1	**Construction Waste Management**, Divert 50%	1
Credit 2.2	**Construction Waste Management**, Divert 75%	1
Credit 3.1	**Resource Reuse**, Specify 5%	1
Credit 3.2	**Resource Reuse**, Specify 10%	1
Credit 4.1	**Recycled Content**, Specify 25%	1
Credit 4.2	**Recycled Content**, Specify 50%	1
Credit 5.1	**Local/Regional Materials**, 20% Manufactured Locally	1
Credit 5.2	**Local/Regional Materials**, of 20% Above, 50% Harvested Locally	1
Credit 6	**Rapidly Renewable Materials**	1
Credit 7	**Certified Wood**	1

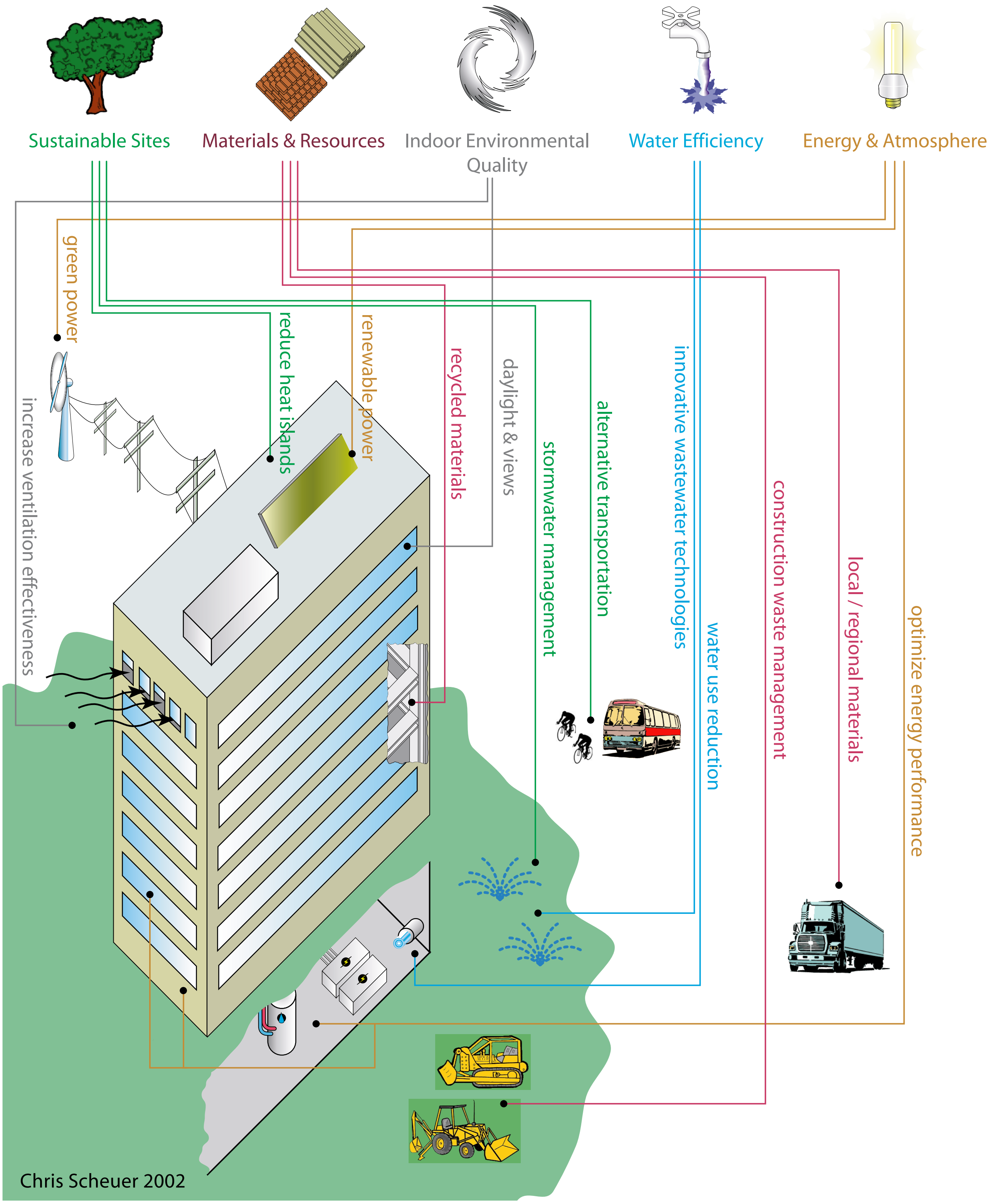
Indoor Environmental Quality		15
Prerequisite	**Minimum IAQ Performance**	x
Prerequisite	**Environmental Tobacco Smoke (ETS) Control**	x
Credit 1	**Carbon Dioxide** (CO_2) **Monitoring**	1
Credit 2	**Increase Ventilation Effectiveness**	1
Credit 3.1	**Construction IAQ Management Plan**, During Construction	1
Credit 3.2	**Construction IAQ Management Plan**, Before Occupancy	1
Credit 4.1	**Low-Emitting Materials**, Adhesives & Sealants	1
Credit 4.2	**Low-Emitting Materials**, Paints	1
Credit 4.3	**Low-Emitting Materials**, Carpet	1
Credit 4.4	**Low-Emitting Materials**, Composite Wood	1
Credit 5	**Indoor Chemical & Pollutant Source Control**	1
Credit 6.1	**Controllability of Systems**, Perimeter	1
Credit 6.2	**Controllability of Systems**, Non-Perimeter	1
Credit 7.1	**Thermal Comfort**, Comply with ASHRAE 55-1992	1
Credit 7.2	**Thermal Comfort**, Permanent Monitoring System	1
Credit 8.1	**Daylight & Views**, Daylight 75% of Spaces	1
Credit 8.2	**Daylight & Views**, Views for 90% of Spaces	1

Innovation & Design Process		5
Credit 1.1	**Innovation in Design**: Specific Title	1
Credit 1.2	**Innovation in Design**: Specific Title	1
Credit 1.3	**Innovation in Design**: Specific Title	1
Credit 1.4	**Innovation in Design**: Specific Title	1
Credit 2	**LEED™ Accredited Professional**	1

Appendix B:

Where Can LEED go?

Conceptual diagram of possibilities for integrating LEED into building design



Chris Scheuer 2002

Appendix C:
SWH LCA Paper

The SWH LCA paper is enclosed in this report as it was submitted to *Energy and Buildings* on December 21, 2000, it has been accepted pending revisions.

Appendix C: Manuscript, Submitted for review to *Energy and Buildings*, Dec. 21, 2001

Life Cycle Energy and Environmental Performance of a New University Building

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Keywords: life cycle assessment, environmental impact, energy consumption, commercial buildings, embodied energy, primary energy, global warming emissions

0.0 Abstract

A life cycle assessment was conducted of a 7,306 m^2, 6-story building with a projected 75 year life span, located on the University of Michigan campus. The bottom three floors and basement are used as classrooms and open-plan offices, the top three floors are used as hotel rooms. A complete inventory of all installed materials and material replacements was compiled, which covers the building structure, envelope, interior structure and finishes, as well as the utility and sanitary systems. Thermal modeling of the use phase was used to determine primary energy consumption for heating, cooling, ventilation, lighting, hot water and sanitary water consumption. Demolition and other end-of-life burdens are also inventoried.

The primary energy intensity over the building's life cycle is 1.15 x 10^6 GJ, or 157 GJ/m^2. Production of construction materials, their transportation to the site as well as the erection of the building accounts for 4.7% of life cycle primary energy consumption. Despite its relatively small mass in the building, copper has the highest material embodied energy of all building materials. All heating, electrical and water services for the building accounts for 95.0% of life cycle primary energy consumption, with water services contributing 6.6% to this subtotal. Building demolition and transportation of waste, contributes only 0.3% of life cycle primary energy consumption. All impact categories measured (global warming potential, ozone depletion potential, acidification potential, nutrification potential and solid waste generation) correlate closely with primary energy demand.

Appendix C: Manuscript, Submitted for review to *Energy and Buildings*, Dec. 21, 2001

1.0 Introduction

1.1 Background

Globally and nationally, commercial buildings contribute significantly to resource consumption, as well as to other environmental impacts, such as air emissions and solid waste generation. For example, 17% of the total year-2000 US primary energy consumption [1] and 13% of the 1999 US 100 year horizon global warming potential was from the commercial sector [2]. Koomey et al. estimate the current trend of carbon emissions from energy consumption in building operations could increase 12% over 1997 levels by 2010 [3]. Construction and demolition waste (C&D) in 1997 amounted to the equivalent of 65% of all Municipal Solid Waste [4], [5].

These and other global environmental and human-health-related concerns have motivated an increasing number of designers, developers and building users to pursue more environmentally sustainable design and construction strategies. However, buildings are exceedingly difficult to evaluate for the following reasons. They are large in scale, complex in materials and function and temporally dynamic due to limited service life of building components and changing user requirements. Their production processes are much less standardized than most manufactured goods because of the unique character of each building. There is limited quantitative information about the environmental impacts of the production and manufacturing of construction materials, or the actual process of construction and demolition.

All of these factors make environmental assessments of the building industry challenging. While there is substantial knowledge about energy- and water-saving strategies for building operations, and federally regulated hazards related to building materials (e.g. Material Safety Data Sheets), there is far less information on the upstream (extraction, manufacturing, transportation) and downstream (deconstruction, disposal) impacts of buildings. Current research is addressing some of these issues. Some studies have been conducted on the relationship between embodied energy in various exterior wall designs and their thermal performance [6]. Much research has gone into developing simulation tools which can measure different operational characteristics [7].

1.2 Life Cycle Perspective

Given the complexities of interaction between the built and the natural environment, life-cycle-assessment (LCA) represents the most comprehensive approach to examining the environmental impacts of an entire building. LCA is a process whereby all the material and energy flows of a system are quantified and evaluated. Typically, upstream (extraction, production, transportation and construction), use, and downstream (deconstruction and disposal) flows of a product or service system are inventoried first. Subsequently, the global and regional impacts are calculated based on energy consumption, waste generation and a select series of other impact categories (e.g., global warming, ozone depletion, nutrification & acidification). Only a full life-cycle perspective allows for a comprehensive assessment of the impact of a system, and an understanding of how impacts are distributed across processes and life cycle stages.

LCA in the construction industry is less developed today than in other industries, but appears to be developing quickly [8]. For example, Cole assessed the impacts of different structural materials, and the relative impacts of embodied and recurring energy [9], [10]. Buchanan and Honey conducted a similar investigation in New Zealand [11]. Only recently have studies taken a full-life-cycle approach to buildings, considering all building materials and operation [12], [13], [14], [15]. In general, most previous studies are not comparable to this LCA because they addressed only a limited set of construction materials/components of the building. A significant area of previous research has been to determine the primary energy consumption for the embodied energy of materials, independent of their application. Others have examined the relationship between embodied energy in construction materials (initial and replacement) and operational energy [13], [6], [16], [17].

Efforts are also underway to establish industry-wide databases of upstream environmental impacts of common construction materials, both in North America[1] and in Australia[2]. These latter initiatives are responding to the need for better data availability and quality for a wider variety of construction materials.

Several software products attempting to incorporate LCA methods into the design and analysis of buildings are now becoming available (e.g., BEES[3], Athena™ database[4], Envest[5]). However, because of data limitations, and due to the large range of construction techniques and material choices, none of these tools are currently capable of modeling an entire building, or computing the environmental impacts from all the phases and processes.

Other limitations of LCA on buildings have also been discussed in the literature. For instance, Reijnders points out that because of the scale and life-span of buildings and the required data resolution, only material and operational impacts can currently be addressed, while topics such as indoor climate, siting and infrastructure are beyond the scope of a typical LCA [18].

The objectives of this paper were to conduct a life cycle assessment of a modern institutional building to evaluate the energy and environmental performance. A University of Michigan building was investigated to address the following specific objectives: compile a comprehensive inventory of installed and replacement building materials, integrate thermal modeling to characterize operational burdens and include modeling of water services. Assessments of primary energy demand global warming potential, ozone depletion potential, acidification potential, nutrification potential and solid waste generation were examined across life cycle phases and among materials.

2.0 Methods

This LCA was conducted in accordance with EPA, SETAC, and ISO standards for Life Cycle Assessments (LCA) ([19], [20], [21], [22]). The Life Cycle Inventory includes the measurement of environmental flows associated with extracting, processing, manufacturing, transporting, constructing and deconstructing the total building material inventory (including manufacturing and installation waste), in addition to a model of building operation and maintenance. The majority of data sets came from the DEAM™ database [23]. Other material production data were taken from two databases by the Swiss Agency for the Environment, Forests and Landscape ([24], [25]), the SimaPro software [26], and from a Franklin Associates report [27].

2.1 Case study building description

The case study building is a 7,306 m^2, 6-story building on the University of Michigan (UM) campus in Ann Arbor, Michigan. The basement, ground floor and floors 2 and 3 are used for classrooms and open-plan offices, while the top three floors are hotel rooms only (floor 4, 5, 6). Table 1 provides a detailed list of building characteristics.

Significant features of this LCA, compared to previous life-cycle energy studies of buildings are the following:

INSERT: TABLE 1, TABLE 2

- Comprehensive and specific material inventory presented in Table 2, which is based on a) design documents (specifications and drawings), b) contractor's records (submittals) and interviews, and c) manual on-site take-offs
- Custom thermal and electrical modeling[6], supported by the mechanical engineer responsible for the building commissioning
- Inclusion of the environmental impacts of hot and cold water consumption and wastewater treatment, based on separate Ann Arbor-specific LCAs[7]

- Site specific accounting for the primary energy requirements for steam and electricity production, based on a mix of site-generated and regional grid electricity.

2.2 Environmental impact categories

The following impact categories were used in order to assess the life cycle environmental impacts of SWH: primary energy consumption, global warming potential, ozone depletion potential, nutrification potential, acidification potential, and solid waste generation. The emission factors used in this study are indicated in Table 3.

INSERT: TABLE 3

Other LCA studies have included human and ecosystem toxicity, as well as resource depletion. In the case of toxicity, both categories were excluded here because of the following reasons:

- Lack of methodological consistency between different studies
- Varying ranges of toxicity factors for a particular emission reported by those studies
- Toxicity fate modeling requires a specificity of emissions release locations that were beyond the scope of this project. (e.g., surface versus ground water releases)

None of the methods reviewed for calculating a “resource depletion” value satisfy the need for a scientifically sound way of interpreting the results. Therefore, resource depletion was not considered for this study as a measurable environmental impact.

2.3 System Definitions, Boundaries and Data Sources

The life cycle phases of the SWH LCA are illustrated in Figure 1. The following sections describe the activities and boundaries for each life cycle phase.

INSERT: FIGURE 1

Only the building itself (structure, envelope, interior and backfill) was included in the material take-off. The temporal basis for this analysis is a 75-year life span. It was assumed that the energy mix for heating, cooling and air conditioning and electrical services would be the same over the entire life span of the building.

For the energy services, and all the construction materials, only the impacts from the actual processes were inventoried (e.g., mining, processing, combustion at power plant), not the impacts from the facilities used for production or manufacturing. Generally this contribution is relatively insignificant. According to [28] and [29] the energy consumed in the power plant during construction is less than 1% of the energy embodied in the fuels combusted in the power plant over its life cycle.

2.3.1 Pre-Use Phase

The pre-use phase in a building's life cycle theoretically encompasses all activities required to design and construct a building. The following activities were inventoried in this study:

<u>Material inventory:</u> The material inventory included burdens associated with the following activities;

a) Raw materials extraction, covering activities such as drilling (e.g., oil, Natural Gas), mining (e.g., iron ore, copper ore, coal), harvesting (e.g., wood) and others (e.g., extraction of synthetic gypsum from power plants), as well as the refinement into engineered materials.

b) Manufacturing, including many of the processing steps required to convert engineered materials or raw materials into particular products (e.g., extrusion of steel or aluminum, injection molding of plastics) [8]

The inventory of the materials installed in SWH was accomplished by mapping the final billing statement from the general contractor to components installed in the building. A complete list of materials was compiled based on construction documents, such as drawings, design specifications, product submittals, and Material Safety Data Sheets (MSDS[9]), as well as through on-site measurements and inquiries with sub-contractors, manufacturers, and UM's Construction Management group.

The total calculated life cycle mass included the initial mass of installed materials and the mass of materials replaced through maintenance and renovations over the life cycle of the building. This mass inventory also incorporates the losses during the manufacture of building components, and those occurring during building construction. In some cases values were found in [30], while for the majority a general 5% loss factor was assumed.

Replacement materials were modeled with the exact same energy and environmental burdens as the initial installed material. No increases in production efficiencies, or material changes over time were modeled. The frequencies of repairs and replacements are based on both, information from UM's Architectural, Engineering & Construction department, and on the information found in [31]. Replacement frequencies used in this study are indicated in Table 4.

INSERT: TABLE 4

The primary material embodied energy on a per-kilogram basis for construction materials used in this study is listed in Table 2. Material embodied energy is the fuel energy content of the resource, expressed as its higher heating value (HHV), plus the energy expended during extraction, refining and production of engineered materials and for the transportation from the site of extraction to the refinery, steel mill or similar operation. Material embodied energy is therefore the sum of feedstock energy and process fuel energies. Note that in this study "total embodied energy" is material embodied energy plus primary energy for transportation and construction, or the total pre-use phase embodied energy.

Two different DEAM™ data sets were used to account for the impacts from electricity use in material production. For those materials processed in the Midwest, a DEAM™ electricity module was utilized which represents the Electricity Cooperative Agreement for Reliability (ECAR) region's grid fuel mix[10]. Electricity consumption for the production of other materials was modeled using the average US electricity grid.

Materials Transportation covers shipping of materials from place of extraction to manufacturing site and from manufacturing site to construction site. The majority of material data sets from DEAM™ already accounted for the transportation energy from the point of extraction (e.g., iron ore), to the manufacturer of the engineered materials (e.g., steel rods). The burdens for transporting materials from the engineered-materials manufacturer to the construction site were modeled using data from suppliers and DEAM™ data sets from 8-ton trucks and 40-ton trucks.

Construction covers electricity used for power tools and lighting, as well as diesel fuel used by heavy equipment at the construction site. Activities include excavation, casting of concrete, erection of the steel structure, hoisting and attaching of pre-cast concrete elements, installation of mechanical and electrical equipment, installation of curtain walls and windows and application of interior finishes (e.g., paints, carpets, suspended ceiling). Additional energy consumption during the commissioning phase of the building is not included. Energy and environmental flows associated with the construction process could not be developed directly, since there was no record of equipment use or operational hours. The Canadian Athena model [32], and work by Cole [33], [9] was therefore used to estimate construction energy. The Athena model predicted total primary construction energy for a steel structure to be 1.2% (90 MJ/m^2 for SWH) of material embodied energy and transportation energy combined. The values in the Cole studies ranged from 6.5% (520 MJ/m^2 for SWH) to 10.0% (750 MJ/m^2 for SWH) of material embodied energy, but included transportation burdens in the construction energy [34]. This study averaged the Athena value with the average of the Cole values to derive 370 MJ/m^2. An estimated additional 370 MJ/m^2 of initial primary material embodied energy was added to account for the nonstructural work, e.g., drywall, flooring, electrical, mechanical. The resulting total primary energy requirements for the construction process were allocated evenly between diesel fuel and electricity to generate site fuel requirements.

Previous LCAs on infrastructure projects have typically not included individual worker transportation. Cole [10] however, did include worker transportation in construction of structural assemblies; hypothesizing a significant impact, based on the number of workers on a building project, their mode of transportation, and the duration of the construction process. Cole found that worker transportation could account for 10 - 80% of total construction energy. This study however did not account for worker transportation, because no actual information for this particular project was available, and worker transportation was not included for other processes used in this study, such as material production.

2.3.2 Use-Phase

Use phase activities consist of heating, cooling and ventilating the building, water supply and water heating, waste water treatment, and lighting and equipment operation. Both, energy and water consumption numbers had to be developed through modeling, because neither space conditioning energy nor water use of SWH is being metered directly.

<u>Energy Inventory:</u> Thermal modeling software was used to determine the annual site energy demand of SWH under Ann Arbor's climatic conditions. Building use characteristics are presented in Table 5. Annual energy demand for heating, cooling, lighting, and miscellaneous electricity was calculated taking into account the use and occupancy patterns of the building spaces, as well as the architectural and mechanical features of the building (i.e., envelope, HVAC, thermal mass, and lighting system and controls). Heat generation impacts from lighting fixtures and equipment[11] on heating and cooling loads were also included. On the central campus of UM, the location of SWH, about 70% of the power (on an annual basis) and all of the steam for heating and cooling is generated in a natural gas (NG) fired combined heat and power plant (CHP). Steam is generated in both, industrial boilers as well as electrical turbines, while chilled water for cooling is produced in a steam-driven absorption chiller with 48% conversion efficiency. 30% of the electricity is provided by the local utility. However the very complex operating conditions at UM's CHP, was simplified for two reasons. First, there is a lack standardization for CHP emissions

allocation procedures. Second, it was felt that a more basic model could be more generally applicable. Operational demand was therefore modeled by using a NG industrial boiler data set for the heating and cooling energy, a NG turbine data set for the campus electrical production, and an ECAR region grid electrical production data set for the fraction provided from the local utility. It would arguably have been less complicated to use only the grid electrical supply in our model, but many large institutional buildings and complexes have their own boilers and onsite power plants, a situation which a straight grid average data set would have failed to represent.

INSERT: TABLE 5

As with materials, the total fuel cycle burdens were considered (i.e., fuel production, processing, and combustion). DEAM™ data sets for the production and combustion of natural gas, diesel oil, and coal were the main source of such data.

Water Inventory: Information about typical SWH occupancy patterns and specific fixture flow rates was used in conjunction with empirical data from other sources regarding the frequency and duration of use of toilets, showers and bathroom sinks as indicated in Table 5. The hot water and cold water consumption figures were combined with results of a recent LCA study on the potable water and wastewater treatment plants in Ann Arbor, MI[12]. Consumption of cold and hot water is primarily due to the 57 hotel rooms on floors four through six. Each of these rooms features one bathtub, one sink, and one toilet. There are only 22 toilet fixtures, 8 urinals, and 18 bathroom sinks in the restrooms of the remaining four floors.

2.3.3 Post-Use Phase

The commonly used terminology for this phase is demolition or decommissioning. The conventional demolition and decommissioning process often results in landfill disposal of the majority of materials. However, some demolition contractors prefer to separate, at the source, recyclables from other materials. In many parts of the country it is profitable to sell concrete, stone, brick, ceramic, metals, glass, carpets, even asphalt roofing shingles to recyclers, which reduces disposal costs and environmental burdens.

Current demolition practices at UM depend on variable factors such as customer demand, contractors chosen, and market prices. The study did not assume a “deconstruction” of the building, which could have made more building components available for reuse. Based on common practices in the industry, this study assumed the recycling of the following materials:

- Concrete, Concrete Masonry Units (CMU), mortar
- Brick, granite, ceramics, mortar
- All metals (steel ducts & pipes, structural steel, duct iron pipes, aluminum window frames, copper tubes & wire, brass, HVAC equipment, faucets & valves)
- Window glass, non-tinted
- Carpets
- Ceiling tiles.

Following the "Second Allocation Method" suggested by the U.S. EPA [19], the recycling of materials benefits the SWH profile only by a reduction in waste generation, not by a reduction in material embodied energy. Future embodied energy benefits would be attributed to whatever product system uses these materials. This study did not credit the SWH system with the feedstock energy of those materials that could be incinerated in a waste-to-heat power plant, as this is not current practice in the Ann Arbor area[13], and may still be unavailable at the end of SWH's lifespan.

As demolition data for SWH were not available, a detailed Canadian study was used to model demolition energy [35]. That study investigated the energy requirements for demolishing only the structure of an office building. The demolition study accounted for the effects of climate (Vancouver vs. Toronto), changing seasonal weather changes, and, the ultimate fate of the demolished materials (reuse vs. recycling). Results were generated for structures made from either wood, steel or concrete. Decommissioning energy for the SWH study was calculated using the energy consumption for a steel structure in Toronto, averaged between the mean summer-high and mean winter-low temperature conditions (130 MJ/m^2 and 220 MJ/m^2 of primary energy respectively, excluding transportation to landfills/recyclers and subsequent landscaping. The total decommissioning energy was doubled in order to account for the removal of all non-structural system (e.g., mechanical, electrical, finishes, cladding, etc.) [35]. All of the demolition energy was considered to be diesel fuel. The total demolition energy of this study therefore was calculated using 350 MJ/m^2.

This study accounted for the differences in transportation distances of demolition materials, depending on their shipment to recyclers or landfills. The distances used, based on available recyclers in the Ann Arbor area, were a)

80 km for steel and iron, b) 48 km for concrete and brick, sand and gravel, c) 320 km for ceiling tile, and c) 8 km to a landfill for all non-recycled materials. The concrete auger cast pilings were assumed to stay in the ground.

2.4 Omissions

The scope of this analysis was limited by omitting the following factors:

- Material production burdens for office equipment, moveable partitions, and furniture
- Street and sidewalk modifications
- Site location and local infrastructure impacts such as utility hookups and related street modifications
- Planning and design of the building (e.g., architect's office heating, lighting, paper for drawings etc.)
- In addition the following materials were omitted due to lack of available data:
  - Materials used during the construction process (e.g. form release oils, plywood for forms, personal protective equipment, signage, solvents used in cleanup).
  - Custodial and small replacement materials (e.g., light bulbs, window glass, air filters, cleaning supplies, toilet paper, soap, small electrical components, such as switches and sensors)

2.5 Other Life Cycle Inventory (LCI) Modeling Assumptions

The LCI was developed from a variety of industry-wide or plant-specific studies, conducted at various times in different regions of the U.S., or internationally. These data sets are the closest representations currently available of the environmental burdens of the materials present in SWH. Since collection of primary data sets for an entire building would have been beyond the scope of this project, such general data represent the best-available information.

Material production and manufacturing process data sets cover about 97.1% (by mass) of the total material requirements of SWH. For another 2.7%, surrogate data were used (e.g. production and manufacture of bottle glass instead of flat glass), or material production data sets alone were used to model fabricated building components (e.g. gypsum and kraft paper for drywall production and manufacture). Finally, 0.2% of the inventoried mass of the building could not be modeled because no data were available.

3.0 Results

Results for each phase will be discussed in terms of energy and material demands first, followed by other environmental impacts such as global warming, nutrification, acidification, and ozone depletion potentials, as well as solid waste generation.

3.1 Pre-Use Phase

The total primary embodied energy was 57 x10^6 MJ over the building lifecycle. This represents only 4.7% of the total life cycle energy demand. Of this, material production required 91% of the pre-use phase, while transportation and construction activities required 4% and 5%, respectively. Replacement of materials accounted for only 1.3% of total life cycle energy demand. Total embodied energy consumption equaled 7.8 GJ/m^2, which falls within the range of "initial embodied energy" of 4 to 12 GJ/m^2 reported by Cole [9]. This wide range may be explained in part by the differences in material production energy used in various studies. By substituting material production energy factors from other studies, material embodied energy in this LCA increased two to three times. One of the primary contributors to this variation is the material production energy factor used for steel. Cole found ranges of 25-39 MJ/kg for steel production published in older reports [33]. Differences in secondary and primary steel production energies as well as age of data could easily account for these ranges. This study uses a range of 14 MJ/kg (hot rolled secondary steel) to 30.6 MJ/kg (galvanized steel), while some other studies used only a single energy factor for all types of steel [11], [8]. Moreover, while Eaton and Amato [8] found no difference in overall material embodied energies between steel and concrete framed buildings, Cole did identify a wide range, with steel being generally lower than concrete [9]. As SWH is a steel-framed building, after adjusting for differences in material production energy the results of this study seem to be consistent with Cole as well as with Honey and Buchanan [11].

A recent study by Worrell et al. found a North American average material production energy factor for cement of 5.4 MJ/kg [36], compared to the DEAM value of 3.7 MJ/kg used in this study. Using the Worrell et al. values, total building life cycle energy consumption would only increase by 0.2%.

INSERT: FIGURE 2, FIGURE 3

The materials and processes (construction and transportation) responsible for 89% of the total embodied energy are shown in Figure 2. The materials from this list only account for 74% of the total building mass. Interestingly,

Figure 3, which illustrates the materials responsible for 98% of the building mass, only account for 63% of total embodied energy. This is primarily due to three factors – a) differences in material production energy factors between materials (MJ/kg), b) the replacement rates for different kinds of materials, and c) the inclusion of transportation and construction energy burdens in the total embodied energy. The materials which dominated the mass of the building have low material production energy factors (see Table 2) and low replacement rates, while the materials which dominate the total embodied-energy have high material production energy factors and in many cases high replacement rates. The result is that copper for phone and electrical wires, which has a material production energy factor of 72 MJ/kg (including extrusion), and a high replacement rate, has the highest contribution to the total embodied energy. The next largest contributors to total embodied energy (with about half of copper's total energy) were cement and sand from concrete and backfill, and EAF steel. These were high due to their large mass. Aluminum, mostly used for window frames, is the fifth most energy intensive material, because of its very high material production energy factor (207 MJ/kg). It is noteworthy that the weighted average of all the material production energy factors in SWH is 3.6 MJ/kg, while the materials with high replacement rates had a weighted average of 77.8 MJ/kg. The combined material embodied energy of nylon, butadiene, polypropylene, rubber and styrene (which are all flooring materials) are second only to copper and like copper they all have higher than average material production energy factors. Clearly replacement rates of materials can cause the embodied energy burden to accumulate quickly. Cole [9] and Howard [37] found higher replacement burdens (5-8% of total life cycle energy) for commercial buildings.

The initial installed mass of SWH is 14,350 tonnes, while the life cycle mass (LCM) over 75 years is 14,750 tonnes. Sand accounts for 55% of the total LCM of SWH, 68% of it is used for backfill and under the foundations, and 32% in concrete. Other concrete ingredients – gravel, cement and water made up the next three most massive materials. Of the steel used in SWH, structural steel accounts for 85%, stair fabrications for 6.6%, while the piping for the sprinkler system is 4.7%. About 68% of the bricks used in SWH are used in the building facing, 32% for the exterior paving, while 88% of the mortar was used in the brick face, the remainder in laying ceramic tile. Flyash, a byproduct from coal-fired power plants, and used to displace some of the cement in concrete, accounts for only 1.1% of the LCM. Copper accounts for only 0.9% of the LCM. There are many other materials that were tracked for this study but their relative contributions were less significant. This analysis shows that the structure and shell of the building (steel frame, concrete, bricks, glass) account for the vast majority of the material burdens. Copper in wiring and water tubing are the only notable exceptions.

The weighted average distance for transportation of materials was only 74 km, with an overall range for all materials between 3 and 1,800 km. Sand and gravel have the shortest distances, while structural and reinforcement steel have among the largest transportation distance. The transportation of materials from manufacturers to the site amounted to 1.5 x 10^9 kgkm, which translates into primary energy requirements of 2.4 x 10^6 MJ. Transportation primary energy demand however represents only 0.2% of the total life-cycle primary energy consumption for SWH. The on-site energy usage for the construction of SWH required 2.7 x 10^6 MJ, which was derived from the total primary energy burden of 57 x 10^6 MJ for initial construction.

3.2 *Use Phase*

The use phase of SWH dominates life cycle energy consumption. Figure 4 shows the building operational demands over a 75-year life span, representing 95% of the primary energy (1.2 x 10^9 GJ). As illustrated, the consumption of NG accounts for 63% of the total life cycle primary energy use, as all the building's heating and cooling, as well as 70% of the electricity is NG-based. The other 30% comes from the local power provider which accounts for 13% of the building operational site energy, and 26% of the primary energy. This is due to the low efficiency of the utility company’s power generation equipment.

INSERT: FIGURE 4

The total site energy demand for heating, cooling, and electrical use, as generated by the thermal model, was 1.34 MJ/m^2/yr (1269 kBtu/m^2/yr). In comparison, the Department of Energy’s (DOE) Commercial Buildings Energy Consumption Survey (“Summary Comparison Table” in [38]) shows 1.10 MJ/m^2/yr for offices, 0.90 MJ/m^2/yr for educational buildings, and 1.45 MJ/m^2/yr for lodging. Considering that SWH is a combination of all three types of uses, the results computed for SWH appear to be consistent.

An unexpected result is that the production and processing of potable water and the treatment of wastewater (75 x 10^6 MJ) is higher than the total embodied energy. Natural gas for hot water heating (71 x 10^6 MJ) accounts for 5.8% of total life-cycle primary energy consumption, while potable water production (2.4 x 10^6 MJ) and wastewater treatment (2.2 x 10^6 MJ) only account for 0.2% each.

It is interesting to compare the initial material embodied energy (without replacements, transportation or construction burdens) invested in a system, and the energy consumed during its use. In SWH, use phase primary energy demand exceeds initial embodied energy after only 2.5 years (3.5 years for total embodied energy). This number corresponds to results from Cole and Eaton, who calculate 2.6 - 4.6 years and 5 - 8 years, respectively [9], [8][14].

3.3 Decommissioning

The energy requirements for decommissioning, demolition and transportation represent only 0.3% (4.0 x 10^6 MJ) of the total life-cycle energy demand. As mentioned above, this study did not credit the SWH system with the potential energy savings from the use of recycled materials recovered from demolition waste, nor did it account for the energy required for the actual recycling of the materials. The resulting reduction in the waste stream however, was accounted for.

3.4 Life Cycle Environmental Impacts

The environmental impacts from SWH followed closely the energy consumption profile in many aspects. The largest contributors in many of the impact categories were emissions related to fossil fuel combustion during the use phase, specifically electrical production. Each impact category characterizes many individual releases, however for the categories used in this study only 1 to 3 pollutants account for the majority of the total impact. Impact assessment results are summarized in Figure 5 with details provided below.

INSERT: FIGURE 5

3.4.1 Global Warming Potential (GWP)

The total life cycle GWP over a 100-year time horizon for SWH was 74 x 10^6 kg of CO_2 equivalent. An overview of the main contributors to SHW's life cycle GWP emissions is shown in Figure 6. CO_2 releases alone accounted for 90% of the total life cycle GWP, while CO_2 releases from the production and consumption of energy and water during building operations alone account for 84%. Material production contributed 6% to the total GWP, while building construction, transportation and decommissioning combined account for only 0.9%.

INSERT: FIGURE 6, FIGURE 7

3.3.2 Ozone Depletion Potential (ODP)

The total life cycle ODP for SWH is 0.4 kg of CFC-11 equivalent. The three air emissions generating 98% of the total ODP were Halon 1301, Methyl Bromide and Methyl Chloride. The distribution of dominant releases is detailed in Figure 7. Similarly to GWP, electricity production for operations is the dominant source, causing 75% of the total life cycle ODP.

3.3.3 *Nutrification Potential (NP)*

The total life cycle NP for SWH is 24 tonnes of PO_4 equivalent, and is based on emissions to air, water and soil. NO_x releases comprise 98% of the total NP. The distribution of the dominant releases is detailed in Figure 8. Once again, operations accounts for the majority of NP, with a total of 85% generated by NO_X releases from the consumption of energy for building operations and water supply. 40% of the NP during operations come from the regional-grid electricity generation, 22% from NG production, 12% from NG combustion in electrical turbines, 8% from NG combustion in industrial boilers. Interestingly, the high levels of NO_x emissions during NG production originate from the many internal-combustion engine powered pump stations that are located along the NG pipelines.

INSERT: FIGURE 8, FIGURE 9

Compared to GWP and ODP, NP is more spread out among the various emissions during operation, though electricity production still dominates with 40% of the total NP. Material production only accounts for 9% of the total life cycle NP, with the bulk of this being from NO_x releases in cement, copper and steel production. Transportation has a higher relative contribution in NP than in GWP or ODP, but still only accounts for 1% of the total NP.

3.3.4 *Acidification Potential (AP)*

The total life cycle AP for SWH is 222 tonnes of SO_2 equivalent. The emissions of SO_X and NO_X to the air during the life cycle account for 95% of the total AP for SWH, with 81% of it coming from energy consumption during the operation of the building. Of this, 61% is caused by SO_X and NO_X emissions released from grid supplied electricity generation, which is regionally coal-dominated. The distribution of dominant releases is detailed in Figure 9. Transportation, building construction and decommissioning combined account for only 2.4% of the life cycle AP. Cement, copper and EAF Steel are the only materials whose production accounts for at least 1% of the total life cycle AP (3.0%, 1.9% and 1% respectively).

3.3.5 *Waste Generation*

The total life cycle waste generation for SWH was 6,862 tonnes, including both, materials that are classified as hazardous or non-hazardous waste. The breakdown of life cycle waste is provided in Figure [1]. Based on the construction site waste factors mentioned earlier, a total on-site waste of 465 tonnes was computed, representing 6.8% of the total life cycle waste generation. This number does not include those ancillary materials consumed at the site that did not become part of the building (e.g. plywood for forms, etc.). Total material production phase waste, which is 34% (2,300 tonnes) of the total life cycle waste burden, was distributed between slags and ashes from energy consumption for material and waste from the manufacturing process (45% and 40% resp.). In fact, waste from production energy for copper, cement and EAF steel accounts for 41% of total material production waste, while manufacturing waste from sand and gravel, in this case most likely mine tailings, account for 37% of the total material production waste.

INSERT: FIGURE 10

More than half of the total life cycle waste generation (55%) originates in the use phase, with contributions of 52% from building energy consumption (3,541 tonnes), and 3.3% from water consumption (225 tonnes). This waste is exclusively related to the production process of the primary fuels used (e.g., mining), and to their combustion to generate steam or electricity (e.g., ashes from coal combustion).

Fuel for transportation produces little waste per unit delivered, so the life cycle waste burdens from transportation of materials seems insignificant with 0.1% of the total (8.7 tonnes).

Materials landfilled from the demolished building at the end of its life accounted for only 8% of the total (550 tonnes). This relatively low value resulted from the assumption that the most massive building materials will be recycled or reused (e.g., concrete, sand, gravel, CMU, Brick, all metals, carpets.

4.0 Conclusions

Life cycle distribution of energy consumption, environmental impacts and solid waste generation is concentrated in the operational phase of a building. In all measurements, except waste generation, operations accounted for more than 78% of the burdens and impacts.

Inclusion of operational water burdens in this LCA alters the life cycle distribution from previous studies. Impacts from water production, heating, and wastewater treatment accounted for between 2-6% of total life cycle impacts.

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[1] Figure: Distribution and primary constituents of solid waste generation

While SWH is, in part, a hotel with greater water consumption than other commercial buildings, complete burdens from potable and wastewater services can be substantial and should not be overlooked in building LCA analyses.

Several materials with high replacement rates were also found to have high embodied energy. Wiring and carpets in particular have high life cycle embodied energies, but can be quite elastic depending on replacement schedules. SWH is an institutional building with replacement schedules significantly lower than those found in other commercial buildings. Even so, the effect of wiring and carpeting replacement is still considerable. More frequent renovations during the life span of a building could quickly raise the total embodied energy and shift the life cycle distribution balance.

4.1 Recommendations

As one of the most obvious steps towards reducing the total life cycle environmental impacts, optimizing the thermal performance and water consumption of the building seems paramount. Not before the magnitude of embodied energy more closely approximates life cycle operational energy, should strategies for reducing embodied energy be emphasized over strategies for improving operational performance. The same holds true regarding the energy demands from transportation and construction activities, except of course for easy-to-implement measures.

A major step in the environmental impact reduction of a building such as SWH, located in the Midwest of the U.S., would be to minimize the purchase of electricity coming from coal-fired power plants. This technology for electrical generation is among the least efficient in terms of primary energy input to delivered energy. Moreover, this study identified it to be the most significant contributor to AP and solid waste generation over the building's life cycle. A shift to power generation technologies, which use cleaner-burning fuels in a more efficient manner (e.g., NG or hydrogen fuel cells) would go a long way in reducing greenhouse gas emissions as well.

One of the first steps to reduce the embodied energy in materials might be to reduce the mass of copper, steel, and aluminum through design modifications. Moreover, using functionally equivalent substitutes or increasing the post-consumer recycled content can yield drastic reductions in embodied energy and associated environmental impacts (e.g., greenhouse gas emissions). Careful consideration of replacement rates for wiring and other high embodied-energy materials can trim life-cycle energy burdens.

In line with a previous LCA study on a residential building by Blanchard and Reppe, carpet seem to offer great potentials for reduction of embodied energy burdens (as well as the associated depletion of non-renewable resources) [13], [14]. Carpets with greater post-consumer recycled content and/or more durable flooring materials, such as cork or wood are a viable alternative in many situations.

With about 6% of the total life cycle energy in SWH being consumed through water use and heating, this aspect certainly demands attention. Hotels and other buildings of high water consumption might focus on the amount and source of water used for flushing toilets (e.g., use of gray or rainwater), and the flow rates of showerheads. Furthermore, significant environmental savings can be achieved through the use of gray-water for landscape irrigation, which would replace the environmental burdens of potable water production.

4.2 Further research

In order to gain a more comprehensive picture of the life-cycle environmental impacts of an institutional building like Sam Wyly Hall, it might be worthwhile including the following categories into the inventory in the future:

- Office furniture and partitions, as those can often have a high replacement rate
- Ancillary materials consumed during building construction
- Custodial materials, and other ancillary materials required for maintenance and upkeep.

Considering the extensive efforts required to establish the material inventory of the entire building, further research on building material environmental issues would greatly benefit from having available the bills of material for various types of buildings, preferably established in collaboration with practicing architects, contractors, and suppliers. For instance, no mass numbers for data and phone wiring was available from the contractors or the electrical engineers. Consequently the number was calculated using national statistics on copper wiring use in buildings[15]. Considering such high-embodied-energy components as copper wiring and carpet, which are subject to a wide range of replacement rates, further research could explore the distribution of replacement cycles in commercial buildings.

Also, in order to improve the data quality of the building's use phase energy modeling, future studies would certainly benefit from the use of either actual, metered consumption numbers, or a more sophisticated thermal model. Moreover, considering how the use phase dominates the life cycle impacts in various impact categories, it would be valuable to run scenarios with alternative sources for heating and cooling energy, or for electricity, such as cogeneration, fuel cells, hydropower and photovoltaics for electricity. Offering similar pollution reduction effects, a scenario on improved thermal performance of the envelope, and improved passive heating, cooling and ventilation methods might better highlight the trade-offs between increased pre-use material requirement and total life cycle savings.

Future LCA studies on buildings could provide a better picture of their full environmental impacts if more scientifically sound methods for assessing the toxicity of emissions, and resource depletion were available. A category on land use, caused by material and energy production processes, in addition to the actual building footprint, might also contribute significantly to the understanding of buildings' overall environmental impacts. Moreover, a more accurate description of buildings' environmental impacts will be made if material data sets are available for a wider variety of construction materials and component manufacturing processes with more region-specific characteristics (e.g., recycled content, transportation distance).

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[1] "US Life Cycle Inventory Database Project" (commissioned by the National Renewable Energy Laboratory)

[2] "Greening the Building Life Cycle", managed by the Centre for Design at RMIT, <http://buildlca.rmit.edu.au/>

[3] "Building for Environmental and Economic Stability" by the National Institute for Standards and Technology, <http://www.bfrl.nist.gov/oae/software/bees.html>

[4] Athena Sustainable Materials Institute, Merrickville, ON, Canada, <http://www.athenasmi.ca>

[5] Building Research Establishment, Garston, U.K., <http://www.bre.co.uk/sustainable/envest.html>

[6] Carrier E-20 and Energy 10

[7] forthcoming, by Center for Sustainable Systems, http://css.snre.umich.edu

[8] The method used for recycled material accounting in this study:
Post-consumer recycled content: wherever possible, only the material collection/transportation and product manufacturing burdens were attributed to the material (i.e., no raw material extraction or processing included);
Post-industrial recycled content (except for true by-products, such as power-plant fly-ash): Allocation of the full raw material extraction and processing/manufacturing burdens PLUS 200% of the processing/manufacturing burdens (reasoning: post-industrial recycled material is a result of manufacturing inefficiencies and requires two cycles of processing and/or manufacturing)

[9] MSDS are government-required documents accompanying hazardous materials, which are traded domestically. They contain information such as the product name and synonyms, manufacturer's contact information, components and contaminants, exposure limits, physical data, fire & explosion hazard data, toxicity data, and health hazard data

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[10] East Central Area Reliability Council (ECAR), http://www.ecar.org/; covers in full or partially the states of Michigan, Ohio, Indiana, Pennsylvania, Kentucky, Maryland, Delaware, West Virginia, Virginia (http://www.eia.doe.gov/cneaf/electricity/chg_str_fuel/html/fig02.html)

[11] I.e., computers, printers, televisions, refrigerators, reading lamps, desk lamps

[12] forthcoming, by Center for Sustainable Systems, http://css.snre.umich.edu

[13] personal communication, Brian Weinert, City of Ann Arbor, Solid Waste Department, and Sarah Archer, Recycling Coordinator, University of Michigan, 10/10/2001

[14] Cole considers embodied energy to include burdens from transportation and construction, but not replacement of materials. Eaton considers embodied energy to include burdens from transportation but not construction or replacement of materials.

[15] Copper Development Association, (http://www.copper.org)

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Figure 1 - Life Cycle Phase Diagram

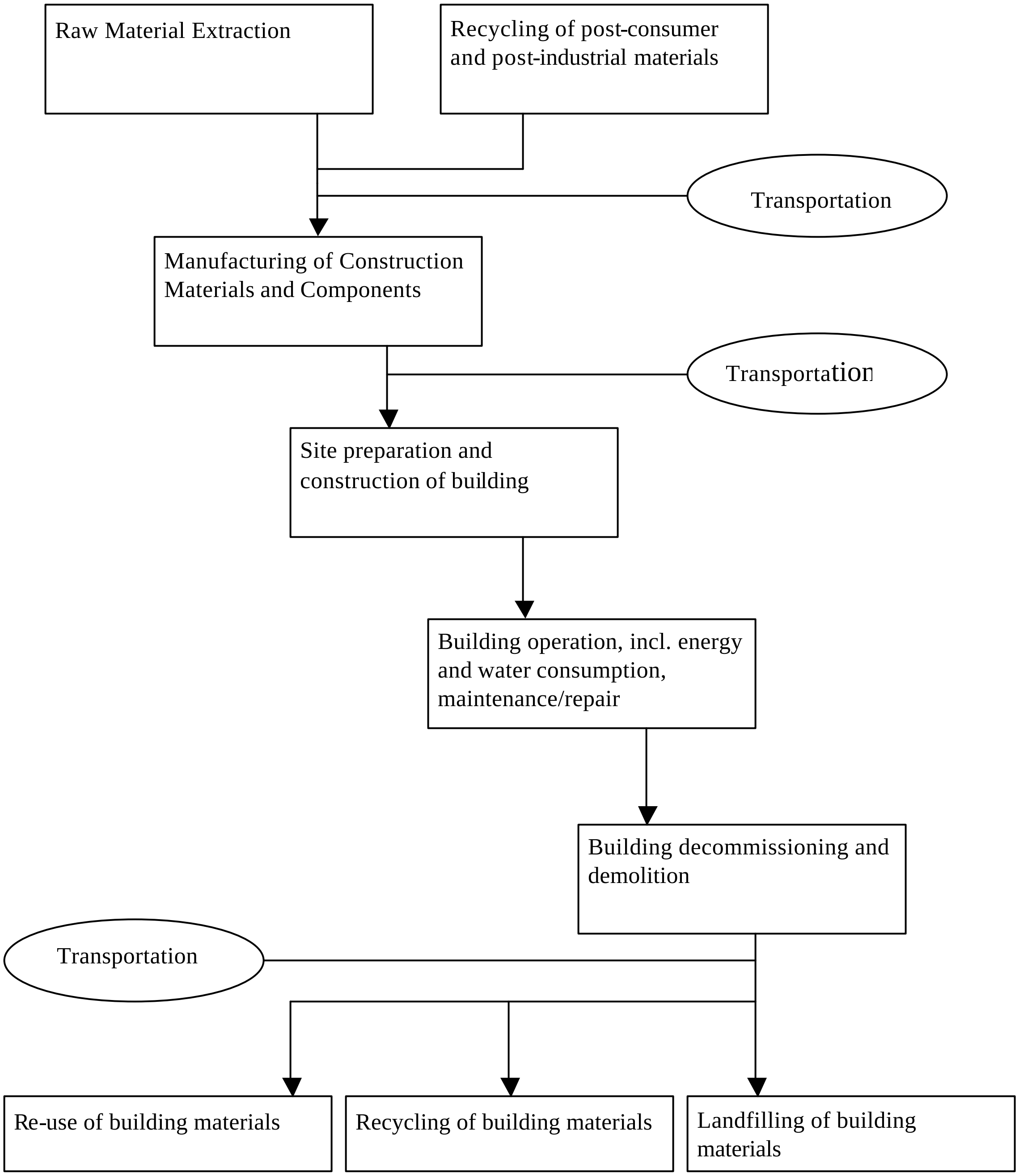


Figure 2 - Materials contributing 89% to the lifecycle material energy burdens

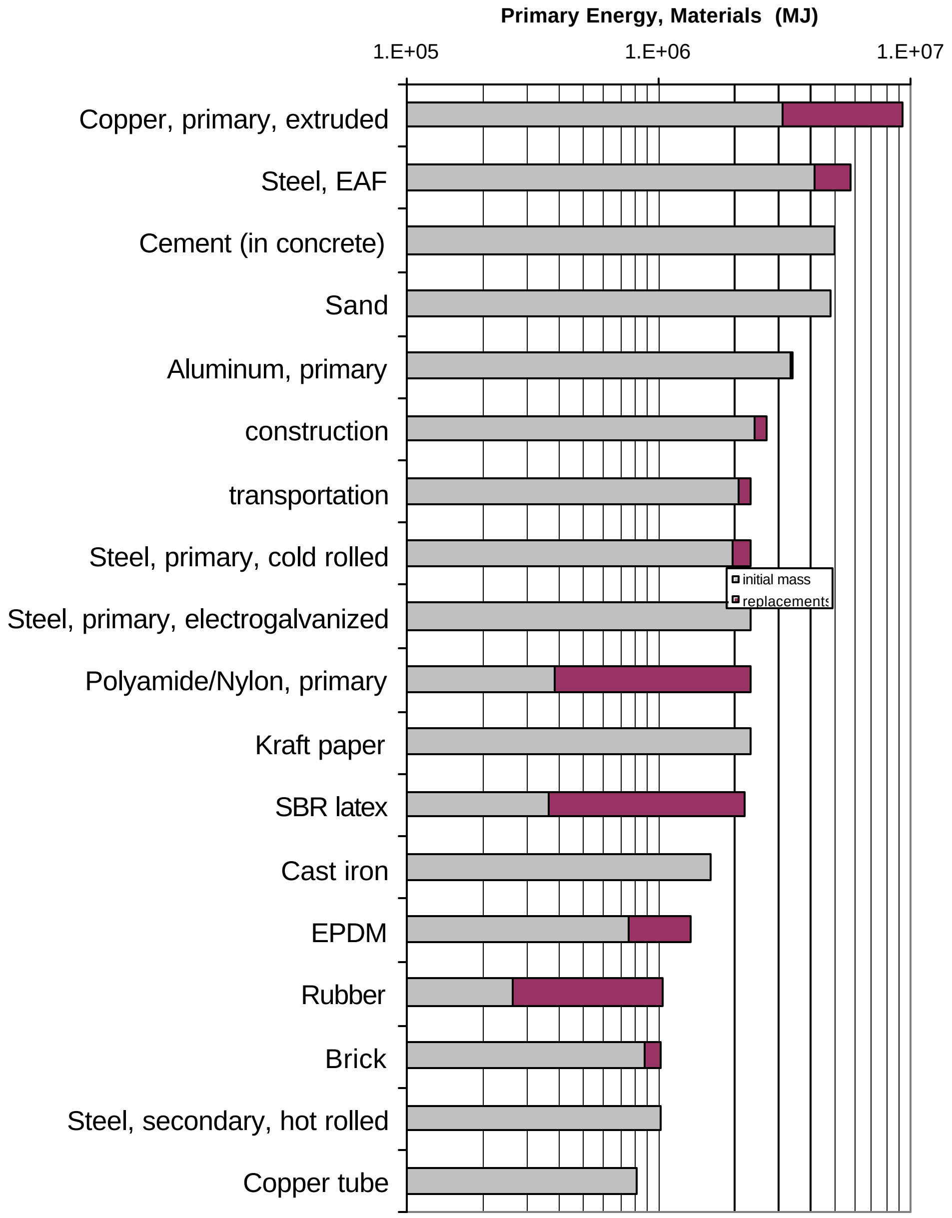


Figure 3 - Materials contributing 98.5% to the initial mass requirements

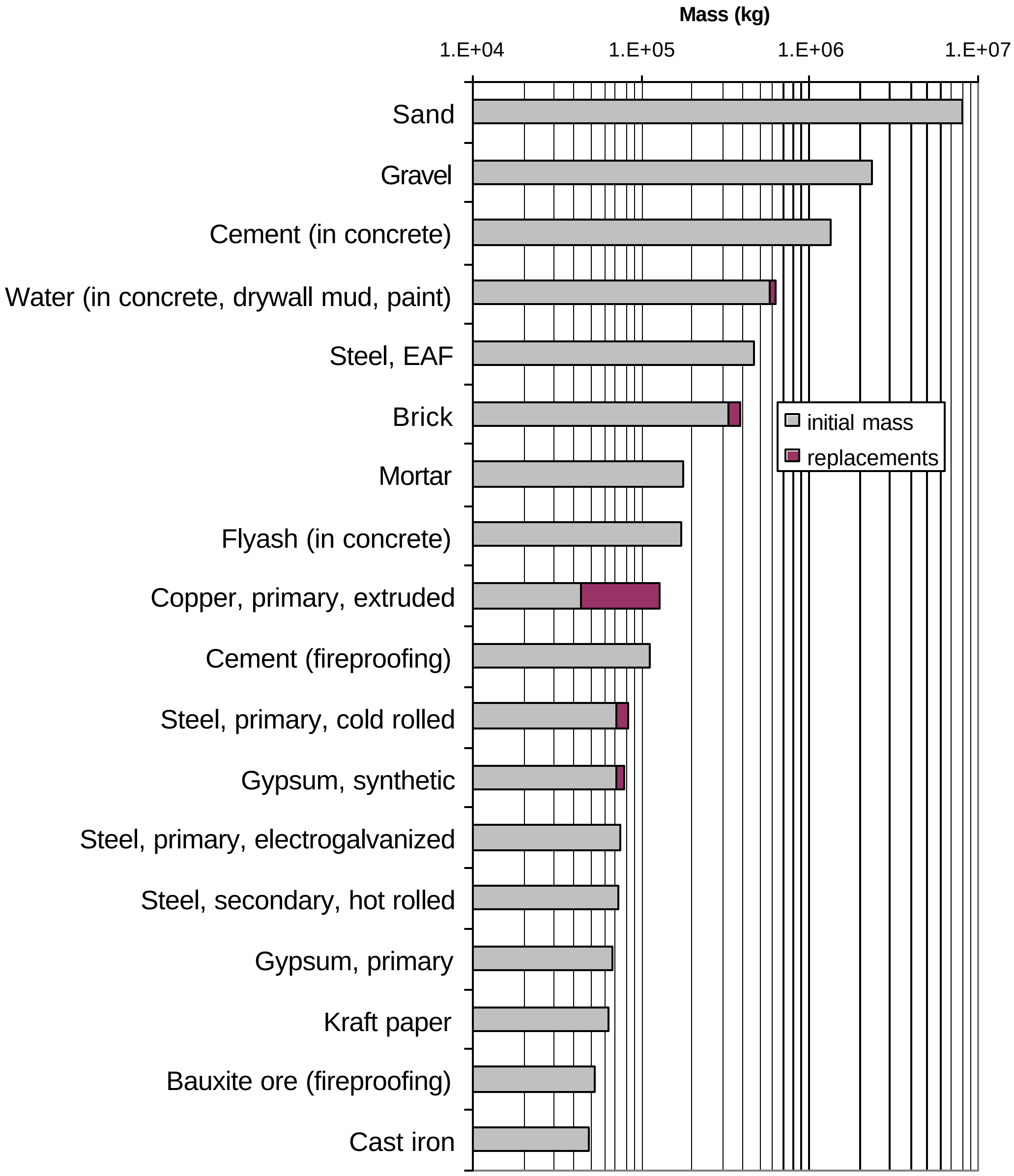


Figure 4 - Life cycle energy distribution

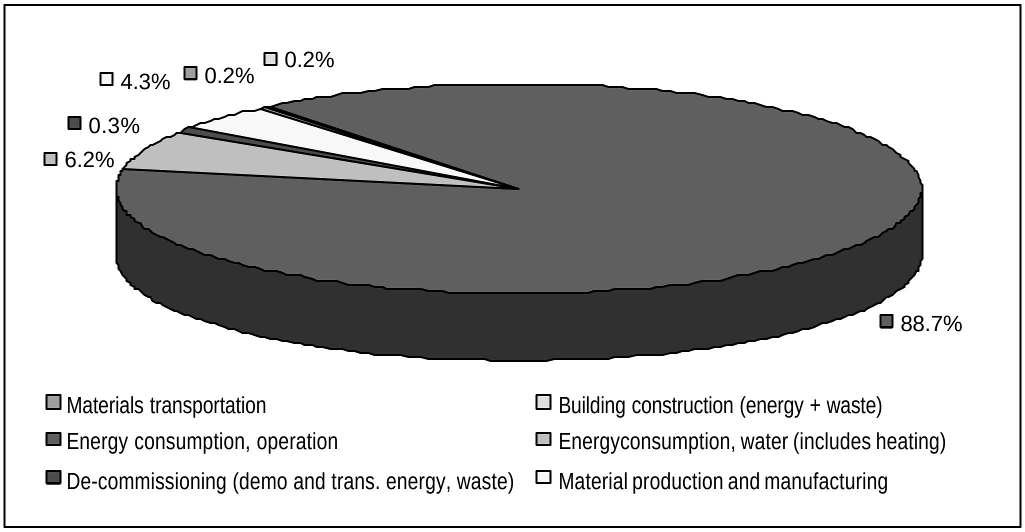
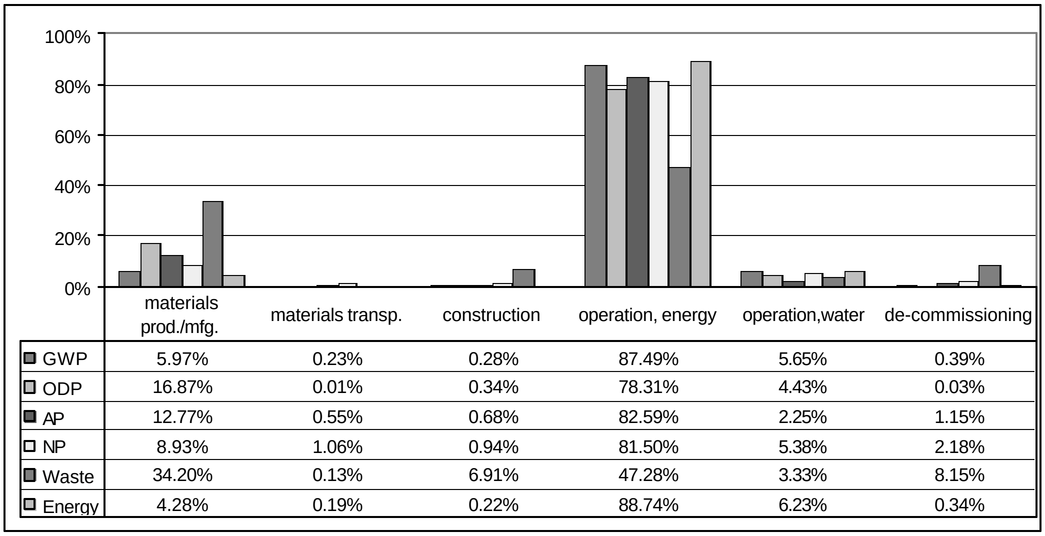


Figure 5 - Life cycle breakdown of environmental impacts



	materials prod./mfg.	materials transp.	construction	operation, energy	operation,water	de-commissioning
GWP	5.97%	0.23%	0.28%	87.49%	5.65%	0.39%
ODP	16.87%	0.01%	0.34%	78.31%	4.43%	0.03%
AP	12.77%	0.55%	0.68%	82.59%	2.25%	1.15%
NP	8.93%	1.06%	0.94%	81.50%	5.38%	2.18%
Waste	34.20%	0.13%	6.91%	47.28%	3.33%	8.15%
Energy	4.28%	0.19%	0.22%	88.74%	6.23%	0.34%

Figure 6 - Distribution and primary constituents of Global Warming Potential

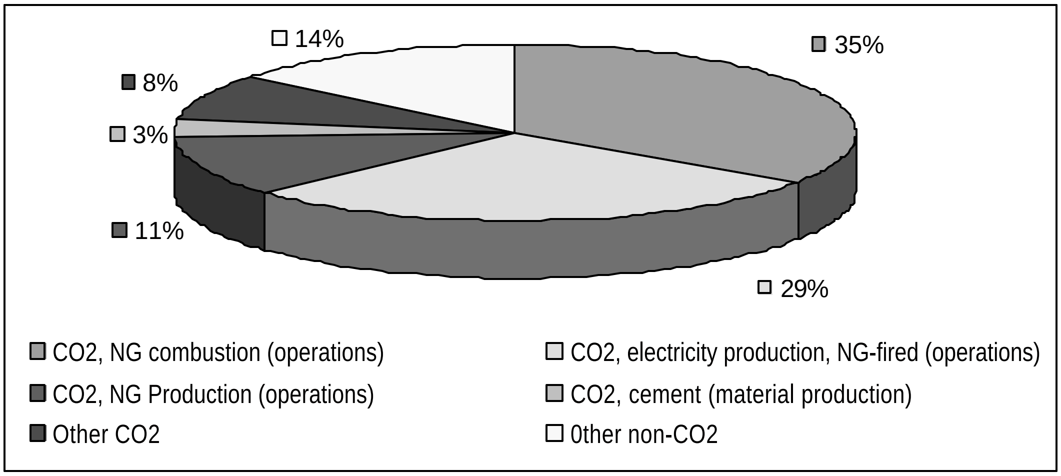


Figure 7 - Distribution and primary constituents of Ozone Depletion Potential

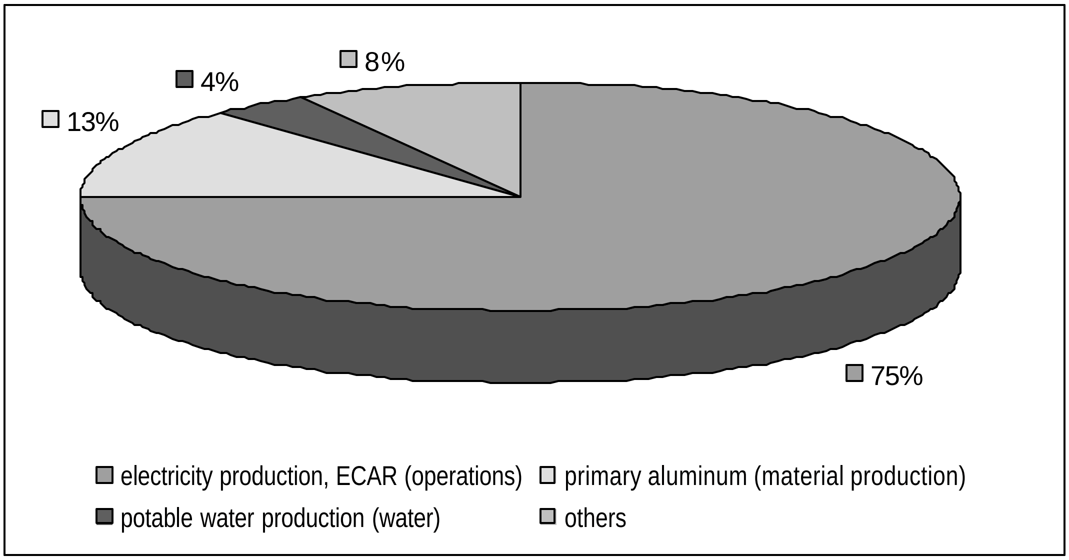


Figure 8 - Distribution and primary constituents of Nutrification Potential

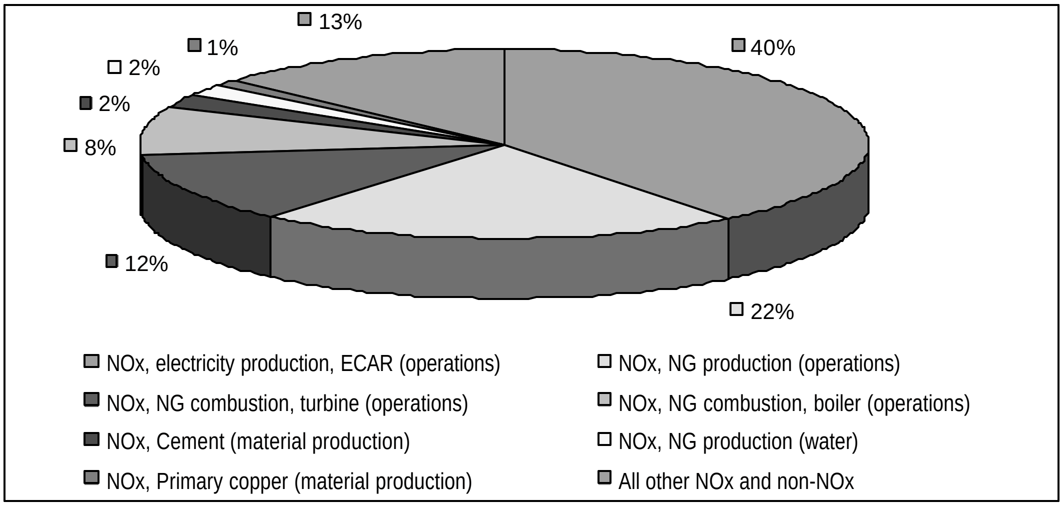


Figure 9 - Distribution and primary constituents of Acidification Potential

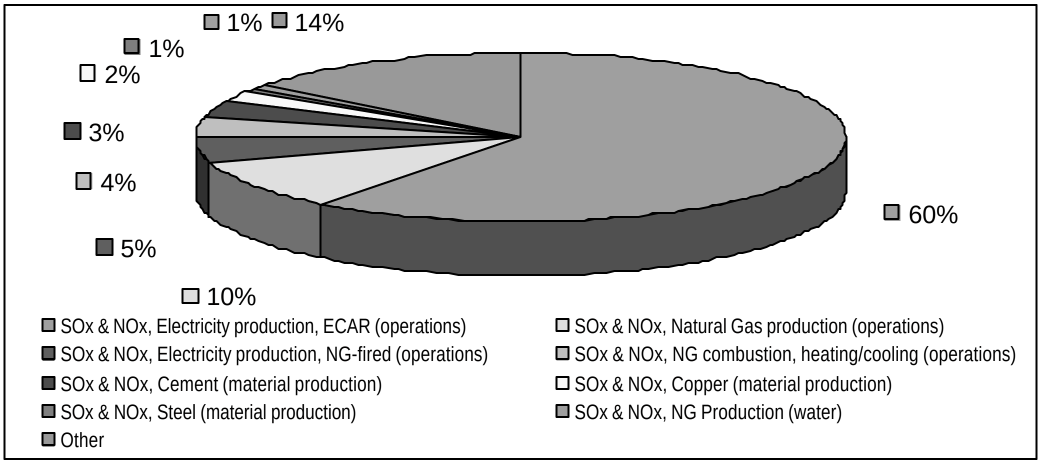


Figure 10 - Distribution and primary constituents of solid waste generation

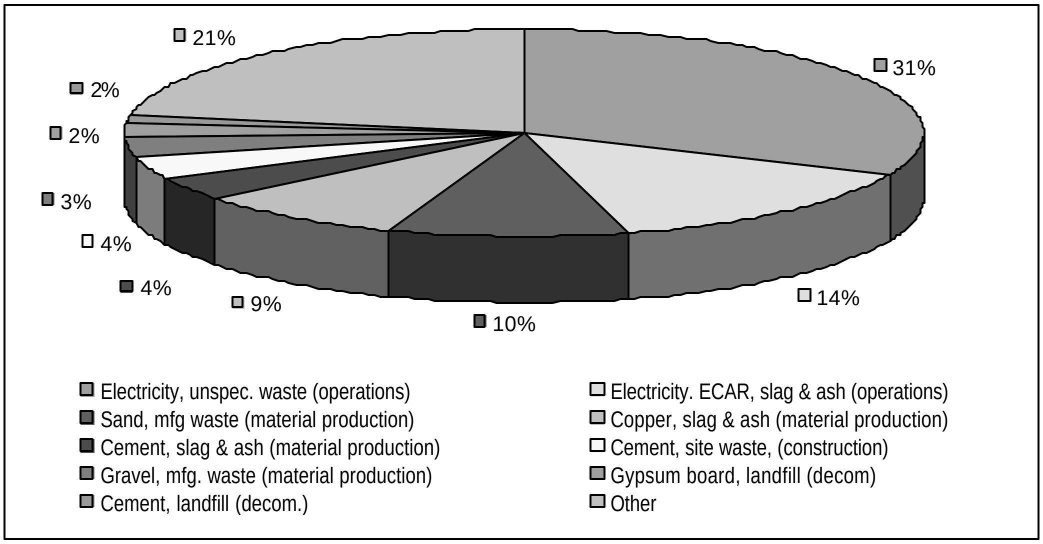


Table 1: Building Characteristics

System	Specifics
Structure	Steel columns and girders throughout
Floors	Ground floor, 2nd and 3rd floor: cast-in place concrete on corrugated, galvanized steel sheets, 4th, 5th and 6th floor: pre-cast concrete, hollow-core elements
Exterior Walls	Ground floor, 2nd and 3rd floor: partially aluminum/glass curtain-wall, partially concrete-masonry unit/brick facing, glass fiber heat insulation, U-value 0.134 W/m^2*K (0.043 Btu/hr*sqft*F) 4th, 5th and 6th floor: pre-cast concrete planks, glass fiber heat insulation
Interior walls	2x4 steel studs (5.1 x 10.2 cm), 1.3 cm (0.5-inch) gypsum board on both sides, 8 cm (3.5 inch) glass fiber sound attenuation
Windows	Aluminum-frame, double-glazed, argon-filled, U-value 1.55 W/m^2*K (0.49 Btu/hr*sqft*F)
Roof	Flat "warm" roof, no skylights, 255 m^2 mezzanine for HVAC equipment, EPDM sheet material on rigid insulation over hollow-core concrete units, U-value 0.067 W/m^2*K (0.021 Btu/hr*sqft*F)
Building orientation	Stretched along North-South axis with an East/West width to North/South width ratio of 1.5 to 1 for the lower three floors, and 3.2 to 1 for the top three floors
Flooring	Offices, class rooms, hallways, hotel rooms: carpet on concrete; Resilient flooring in various spaces: PVC tile and sheet flooring, ceramic tiles; stairs: rubber and carpet
Ceilings	Suspended ceilings, steel grid, 68% recycled content ceiling tiles (synthetic gypsum, steel mill slag, corn starch, perlite, paper)
Lighting	115 tracklights (compact fluorescent lamps), ceiling light fixtures (fluorescent tube): 537 "1x4" (120 cm), 38 "2x4", 158 "2x2" (60 cm), 88 wall washers (halogen), 82 "1x4" surface mounted (fluorescent), 304 down-lights (halogen), 181 down-lights (compact fluorescent), 65 "2x4"chain-hung fluorescent, 186 wall scones (incandescent), 57 ceiling-mounted hotel room fixtures (halogen), 114 reading lamps (57 incandescent, 57 fluorescent)
Lighting controls	All manual
HVAC/Heating	Steam from central power plant (CPP), a Natural-Gas-fired industrial boiler[1]
HVAC/Cooling	Chilled water, generated in external chiller plant, powered by CPP steam
HVAC equipment	Variable Air Volume boxes with reheat coil for zone heating/cooling; variable frequency drive motors on supply and return air fans
HVAC distribution	Air ducts in lower 4 floors; hot and chilled water with fan coils in top three floors (hotel rooms)
HVAC controls	air economizer (integrated enthalpy) and night-flushing with outside air for free cooling, CO2 sensors for fresh-air supply (only partially modeled due to software limitations)
Electricity	70% from external, regional utility company, 30% from CPP
Potable water	100% from municipal water treatment plant (Ann Arbor, MI)
Water heating	Steam from Central Power Plant
Waste water	Municipal waste water treatment plant
Rainwater	100% into city's storm sewer system, and further into the Huron River.

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[1] The Central Power Plant (CPP) at the University of Michigan is in fact a cogeneration plant with about 80% overall efficiency, featuring NG-fired boilers and electrical turbines. For reasons of simplifying the model, and to better be able to compare the results to similar studies and buildings, the use of industrial boilers for steam generation only, and of electrical turbines for power generation only was modeled.

Table 2: Life cycle mass and primary embodied energy of SWH building materials

Material	Total life cycle mass	Embodied energy factor*	Material	Total life cycle mass	Embodied energy factor*
	(kg)	(MJ/kg)		(kg)	(MJ/kg)
Sand	8,047,007	0.6	Limestone	12,713	0.1
Gravel	2,361,643	0.18	Copper tube	12,508	65.8
Cement (in concrete)	1,332,745	3.74	Clay (in fire proofing)	11,725	33.08
Water (in concrete, drywall “mud”, paint)	629,796	0.19	Paper, secondary	10,320	6.93
Steel, EAF	471,413	12.3	Polypropylene	10,183	74.95
Brick	386,150	2.67	Polyisocyanurate	9,942	70
Mortar	178,487	0.01	Titanium Dioxide	9,061	73.82
Flyash (in concrete)	169,476	No data	Rubber	7,316	143
Copper, primary, extruded	130,008	71.58	EPDM	7,282	179.12
Cement (in fireproofing)	111,182	3.74	Kaolin (in ceiling tiles)	6,880	1.29
Steel, primary, cold rolled	83,894	28	Ceramic and quarry tile	6,082	5.5
Gypsum, synthetic	79,680	No data	Polystyrene	5,636	94.38
Steel, primary, electro-galvanized	76,107	30.63	Glass fiber, post-industrial secondary	5,086	11.88
Steel, secondary, hot rolled	72,182	14.09	Wood	3,187	10.75
Kraft paper	66,358	36.74	PVC, flooring	2,529	50.14
Gypsum, primary	65,919	0.9	Polyamide, secondary	2,064	No data
Bauxite ore (in fireproofing)	52,538	0.6	PVC, pipes, wiring	1,829	60.72
Cast iron	48,565	32.84	Brass	1,430	239
Glass	47,083	6.83	Ethylene Glycol	653	83.69
Granite	35,194	0.1	Argon	439	6.8
SBR latex	31,490	69.95	Waxes	371	52.01
Glass fiber, primary	21,010	17.55	Acrylate lacquer (carpet grout)	337	30.81
Polyamide/Nylon, primary	18,574	124.89	Xylene (in paint & waterproofing)	267	60.2
Starch	18,414	14.29	Asphalt	70	50.17
Steel, stainless	16,817	8.16	Polyethylene	63	79.45
Aluminum, primary	14,603	206.97	Toluene Diisocyanate	38	100.96
Paver tile	13,774	0.52	Toluene	4	67.86

*…Includes raw material extraction, material production, and transportation between these two steps

Table 3: Emission factors

Impact category, Emission	**Emission factor (source** [Leiden University, 2000 #211]**)**
GLOBAL WARMING POTENTIAL	**CO^2 equivalent**
Carbon Dioxide (CO2, fossil)[a]	1
CFC 11 (CFCl3)[a]	4000
CFC 114 (CF2ClCF2Cl)[a]	9300
CFC 12 (CCl2F2)[a]	8500
CFC 13 (CF3Cl)[a]	11700
Halon 1301 (CF3Br)[a]	5600
HCFC 22 (CHF2Cl)[a]	1700
Methane (CH4)[a]	21
Nitrous Oxide (N2O)[a]	310
Trichloroethane (1,1,1-CH3CCl3)[a]	110
OZONE DEPLETION POTENTIAL	**CFC-11 equivalent**
CFC 11 (CFCl3)[a]	1
CFC 114 (CF2ClCF2Cl)[a]	0.85
CFC 12 (CCl2F2)[a]	0.82
Halon 1301 (CF3Br)[a]	12
HCFC 22 (CHF2Cl)[a]	0.04
Methyl Bromide (CH3Br)[a]	0.4
Methyl Chloride (CH3Cl)[a]	0.02
Trichloroethane (1,1,1-CH3CCl3)[a]	0.12
ACIDIFICATION POTENTIAL	**SO2 equivalent**
Ammonia (NH3)[a]	1.6
Nitrogen Dioxide (NO2)[a]	0.5
Sulfur Dioxide (SO2)[a]	1.2
NUTRIFICATION POTENTIAL	**PO4 equivalent**
Ammonia (NH3)[a, w]	0.35
Nitrogen Oxide (NO2)[a]	0.13
Nitrogen (N)[s, w]	0.42
Nitrate (NO3-)[w]	0.1
Phosphorus (P)[a, s, w]	3.06
Phosphates (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)[w]	1
a…air emissions s…soil emissions w…water emissions	

Table 4: Lifespan of materials used in the study

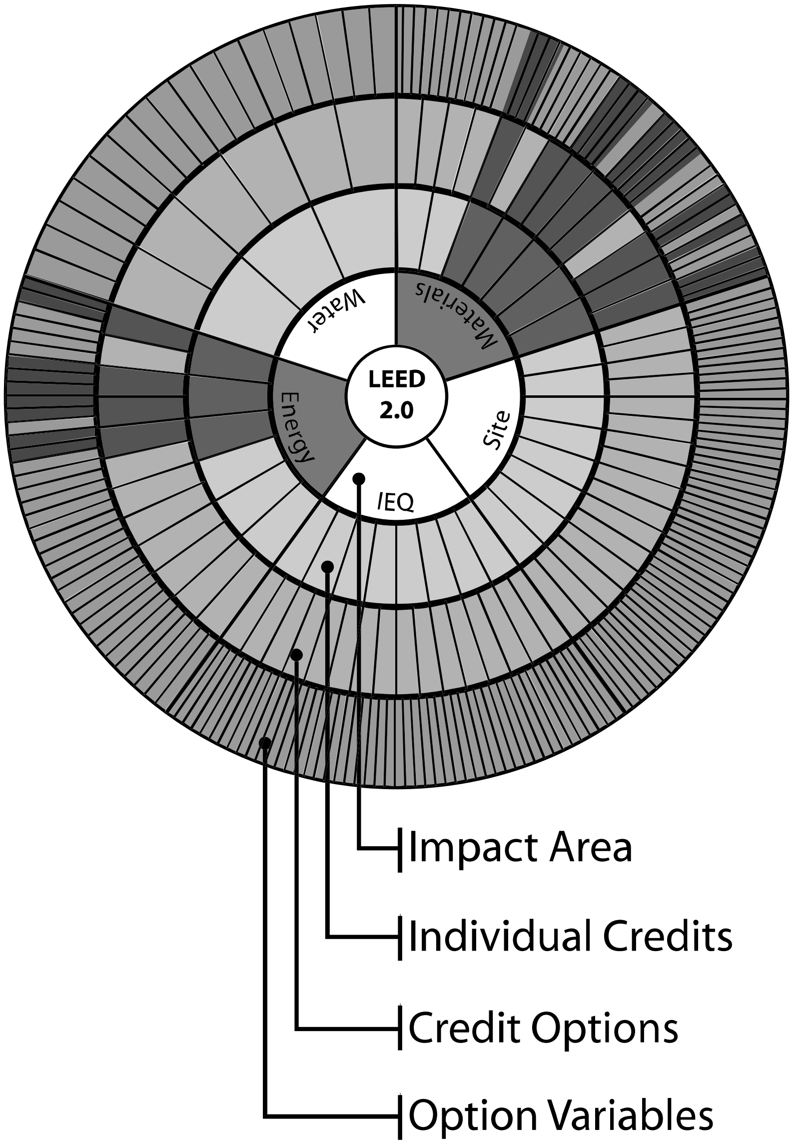
Component	Life span (years)		Component	Life span (years)
BUILDING SHELL AND STRUCTURE			MECHANICAL, ELECTRICAL, PLUMBING	
Concrete foundation	75		Steel air ducts (sheet metal)	75
Structural steel	75		Duct liner, acoustic	75
Fire proofing for structural steel	75		Pipe, copper	75
Steel stairs	75		Sewer pipes	75
Face brick	75		Pipe, black steel	50
Concrete masonry units (CMU)	75		Pipe, cast iron	50
Waterproofing, foundation walls	75		Pipe, PVC	50
Thermal insulation	75		Restroom sinks	50
Floor slabs on steel deck	50		Urinals	50
Hollow core plank, exterior wall	50		Toilet fixtures	50
Hollow core plank, floors	50		Sprinkler system pipes	50
Curtainwall, Al panels	40		Elevators	40
Curtainwall, glazing	40		Radiators (base board)	40
Operable Al-frame windows	40		Phone and data wiring (copper)	25
Stone, exterior steps	40		Sprinkler heads	25
Roofing insulation	40		Fan coils	20
EPDM single-ply roofing	35		Air-handling unit, roof	20
Exterior brick pavers	30		Shower tubs	20
Waterproofing, loading dock	20		Faucets, sink	20
BUILDING INTERIOR AND FINISHES			Faucets, shower	20
Wood paneling	75		Flush valves urinal	20
Door frames	75		Flush valves toilet	20
Interior column covers (stainless)	75			
Stone, base material, interior	75			
Drywall (gypsum board, steel studs)	75			
Ceramic floor tile	75			
Wooden doors	50			
Metal doors	50			
Toilet compartments (stainless steel)	50			
Treatment of wood paneling	35			
Joint sealer	25			
Acoustical wall panels	20			
Ceiling tiles	20			
Raised rubber tile	18			
Sheet vinyl	18			
Vinyl composition tile (VCT)	18			
Carpet (tile & broadloom)	12			
Paint on drywall	5			

Table 5: Operational characteristics of Sam Wyly Hall

GENERAL		
Occupancy office spaces, weekdays (249/year)	70 (50% female, 50% male)	Building manager
Occupancy office spaces, weekends (96/year)	10 (50% female, 50% male)	Building manager
Occupancy hotel rooms, weekdays	116 (50% female, 50% male)	Building manager
Occupancy hotel rooms, weekends	116 (50% female, 50% male)	Building manager
ENERGY CONSUMPTION		
Area of spaces used as classrooms	2,791 m^2 (30,043 sqft)	Construction drawings
Area of spaces used as offices	2,405 m^2 (25,889 sqft)	Construction drawings
Area of spaces used as hotel	2,110 m^2 (22,713 sqft)	Construction drawings
Internal electrical load (lighting & computer)	15 – 18 W/m^2 (1.4 – 1.7 W/sqft)	Construction drawings and design specifications
Temperature set point, office/classroom	24 °C (75 °F)	Building commissioning engineer
Temperature set back, office/classroom	24 °C (75 °F)	Building commissioning engineer
Temperature set point, hotel rooms, heating	24 °C (75 °F)	Building commissioning engineer
Temperature set back, hotel rooms, heating	24 °C (75 °F)	Building commissioning engineer
Temperature set point, hotel rooms, cooling	22 °C (72 °F)	Building commissioning engineer
Temperature set back, hotel rooms, cooling	22 °C (72 °F)	Building commissioning engineer
Effective leakage area total	1.6 m^2 (2500 in^2)	[Chalifoux, 2001 #218]
Air exchange rate modeled, classrooms/offices	0.51 exchanges/hr	Building commissioning engineer
Air exchange rate modeled, hotel rooms	0.48 exchanges/hr	Building commissioning engineer
WATER CONSUMPTION		
Number of urinal uses / day, males (offices/classrooms) *	2	Inferred from [AWWA, 1999 #208] and [Del Porto, 1999 #206]
Number of urinal uses / day, females (offices/classrooms) *	0	Inferred from [AWWA, 1999 #208] and [Del Porto, 1999 #206]
Number of toilet uses / day, females (offices/classrooms) *	3	Inferred from [AWWA, 1999 #208] and [Del Porto, 1999 #206]
Number of toilet uses / day, males (offices/classrooms) *	1	Inferred from [AWWA, 1999 #208] and [Del Porto, 1999 #206]
Number of toilet uses / day, females (hotel rooms) **	5	[AWWA, 1999 #208], [Del Porto, 1999 #206]
Number of toilet uses / day, males (hotel rooms) **	5	[AWWA, 1999 #208], [Del Porto, 1999 #206]
Urinal water consumption	3.79 liters/flush (1 gal/flush)	Building design specifications SWH
Toilet water consumption	13.25 liters/flush (3.5 gal/flush)	Building design specifications SWH
Number of sink uses / day (offices/classrooms)	4	Informal survey
Number of sink uses / day (hotel rooms)	2	Informal survey
Number of shower uses / day (hotel rooms)	1.5	Informal survey
Duration of sink uses (offices/classrooms)	0.25 min (15 sec)	Informal survey
Duration of sink uses (hotel rooms)	1 min (60 sec)	Informal survey
Duration of shower uses (hotel rooms)	5 min	Informal survey
Flow rate restroom faucet (offices/classrooms + hotel rooms)	9.46 liters/min (2.5 Gal/min)	Building design specifications SWH
Flow rate showers (hotel rooms)	9.46 liters/min (2.5 Gal/min)	Building design specifications SWH
*…Accounting for full-time office workers **…Hotel guests are present in the office/classroom spaces during the day, and are therefore a		

Appendix D:
Conceptual Diagram of LEED Program Scope and Research Scope

Note: Light gray areas are a representation of LEED program scope at various levels of detail. Dark Grey represents the scope of this research project at each level of detail.



Appendix E:
Material Cost Summaries* [52]

Work description	**Cost**
loading dock equip	$3,850
Matal wall louvers	$4,700
Expansion joints	$5,000
wire mesh	$6,000
entracnce mats	$6,500
EIFS	$7,200
Fire protection spec.	$7,600
coiling doors	$8,000
Auto Sliding Doors	$8,160
toilet compartments	$17,600
Access flooring	$18,800
operable partitions	$19,520
Joint sealers	$20,000
Acoustical wall panels	$21,000
Steel Doors and Frames	$25,000
visual display boards	$34,150
projection screens	$39,600
Acoustical Ceilings	$58,502
Wood Doors	$65,000
Drywall Glass Fiber Gypsum	$72,330
Special coatings	$76,591
Hardware	$88,440
Roofing & Sheet Metal, Roof	$90,200
brick and tile	$111,680
metal wall panels	$126,500
Reinforcing Steel	$184,000
Millwork	$242,348
Resilant Flooring/carpeting	$270,150
masonry	$288,120
drywall and acoustical	$295,256
metal fabs	$528,900
Precast plank	$581,300
Glass, Glazing, Aluminum	$707,790
foundation and earth work	$834,236
structural steel	$1,103,153
Total	**$5,977,176**
*Excludes Electrical, Plumbing and Mechanical Materials	

Appendix F:
RCR Tables

Option 1

Material	Material Cost	PC	PI	RCV
concrete work	$568,236		2%	$32,674
wire mesh	$6,000	25%		$7,500
Precast plank	$581,300		2%	$33,425
block material	$114,720		2%	$6,596
Structural Steel	$1,023,528	25%		$1,279,410
Steel Decking	$79,625	25%		$99,531
metal fabs	$528,900	25%		$661,125
Millwork	$242,348			$0
Steel Doors and Frames	$25,000	25%		$31,250
Roofing & Sheet Metal, Roof	$90,200		4%	$10,122
metal wall panels	$126,500	25%		$158,125
Sound proofing	$190,000		70%	$332,500
metal studs	$95,656	25%		$119,570
building insulation	$9,600		70%	$16,800
Drywall Glass Fiber Gypsum	$72,330			$0
Acoustical Ceilings	$58,502	18%	18%	$78,398
Tileing	$79,680	75%		$298,800
carpeting	$247,168	3%		$38,311
Painting	$52,335	65%		$170,089
total RCV				$3,374,226
total materials costs				$5,977,176
LEED RCR				**56%**

Option 2

Material	Material Cost	PC	PI	RCV
concrete work	$568,236		6%	$83,815
wire mesh	$6,000	25%		$7,500
Precast plank	$581,300		6%	$85,742
block material	$114,720		6%	$16,921
Structural Steel	$1,023,528	25%		$1,279,410
Steel Decking	$79,625	25%		$99,531
metal fabs	$528,900	25%		$661,125
Millwork	$242,348			$0
Steel Doors and Frames	$25,000	25%		$31,250
Roofing & Sheet Metal, Roof	$90,200		4%	$10,122
metal wall panels	$126,500	25%		$158,125
Sound proofing	$190,000			$0
metal studs	$95,656	25%		$119,570
building insulation	$9,600			$0
Drywall Glass Fiber Gypsum	$72,330		41%	$73,777
Acoustical Ceilings	$58,502	18%	18%	$78,398
Tileing	$79,680			$0
carpeting	$247,168	43%		$531,411
Painting	$52,335			$0
total RCV				$3,236,697
total materials costs				$5,977,176
LEED RCR				**54%**

Option 3

Material	Material Cost	PC	PI	RCV
concrete work	$568,236		6%	$83,815
wire mesh	$6,000	25%		$7,500
Precast plank	$581,300		6%	$85,742
block material	$114,720		6%	$16,921
Structural Steel	$1,023,528	25%		$1,279,410
Steel Decking	$79,625	25%		$99,531
metal fabs	$528,900	25%		$661,125
Millwork	$242,348		70%	$422,897
Steel Doors and Frames	$25,000	25%		$31,250
Roofing & Sheet Metal, Roof	$90,200		4%	$10,122
metal wall panels	$126,500	25%		$158,125
Sound proofing	$190,000		70%	$332,500
metal studs	$95,656	25%		$119,570
building insulation	$9,600		70%	$16,800
Drywall Glass Fiber Gypsum	$72,330		41%	$73,777
Acoustical Ceilings	$58,502	18%	18%	$78,398
Tileing	$79,680	75%		$298,800
carpeting	$247,168	43%		$531,411
Painting	$52,335	65%		$170,089
total RCV				$4,477,783
total materials costs				$5,977,176
LEED RCR				**75%**

Appendix G:
SWH – ASHRAE requirements

U.S. Climatic data - Table D.1	
Location	Detroit
HDD18	3426
CDD10	1692
Heating Design Temp (99.6%)	-18
Cooling Design Temp, drybulb 1%	31
Cooling Design Temp, wetbulb 1%	22

Building Envelope Requirements U-values (W/m^2 * $^?$C) - Table B.17		
Assembly	**SWH Base**	**ASHRAE max. (fixed) and SHGC (all and north)**
Roof -insulation entirely above deck	0.04	0.37
Walls above grade -mass	0.07	0.71
Walls below grade -Below grade wall	0.15	0.39
Floors -Mass	0.78	0.51
Opaque doors -Swinging	0.88	4.05
Assembly	**SWH Base**	**ASHRAE max. (fixed) and SHGC (all and north)**
Vertical glazing -20.1-30% (SWH=24%)	1.47 (pane) 2.781 (frame)	3.29

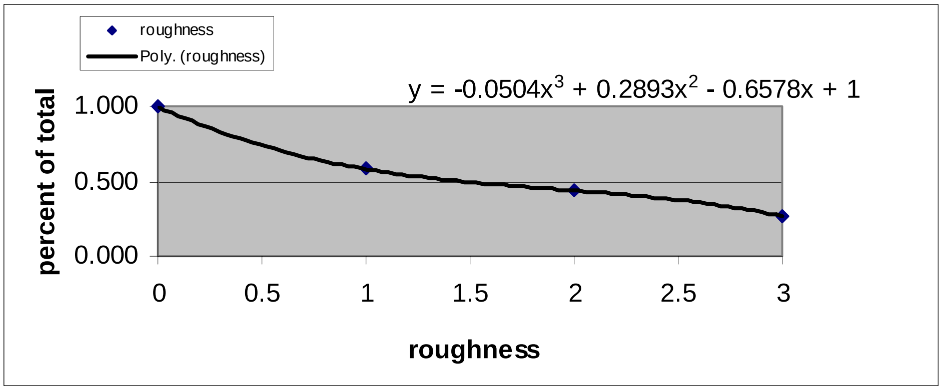
Equipment, Min. Efficiency Requirements - Table 6.2.1C, Table 6.2.1F, Table 7.2.2		
Equipment type	**SWH Base**	**ASHRAE min.**
Boiler, gas fired	80%	80%E_c
Gas storage water heater	73%	80% E_t
Absorption double effect direct-fired	0.93	1.00 COP

Lighting Power Densities (W/m^2) - Table 9.3.1.2

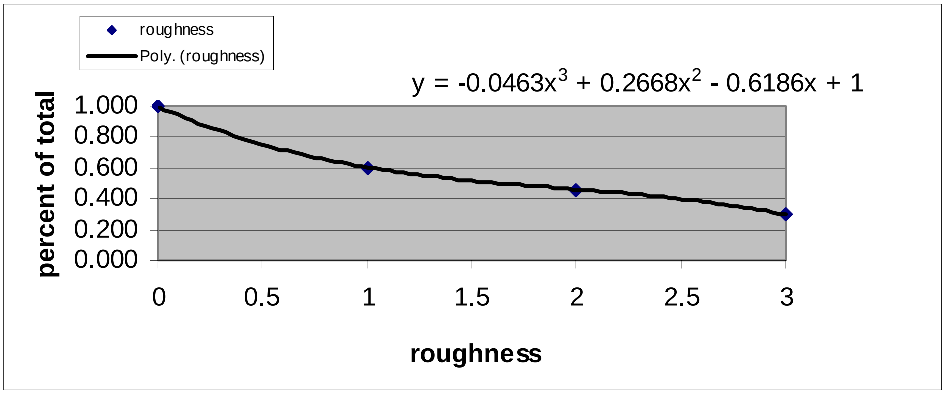
bldg tpe	office enclosed	office open	conference meeting	classroom lectureq	Lobby	lounge/ reception	food prep	restroooms	corridor	active storage	electrical mechanical	guest rooms	total
School/Univ, office, Hotel	17	14	16	17	19	15	23	10	8	12	14	26	
SWH % space	7%	15%	10%	12%	4%	5%	3%	3%	15%	4%	4%	19%	
SWH wattage	1.11	2.12	1.5271	2.027	0.7	0.703	0.8	0.3	1.23	0.5	0.534	4.83	**16.36**
												SWH base case	**15.1**

Appendix H:
Wind Function Tables[66]

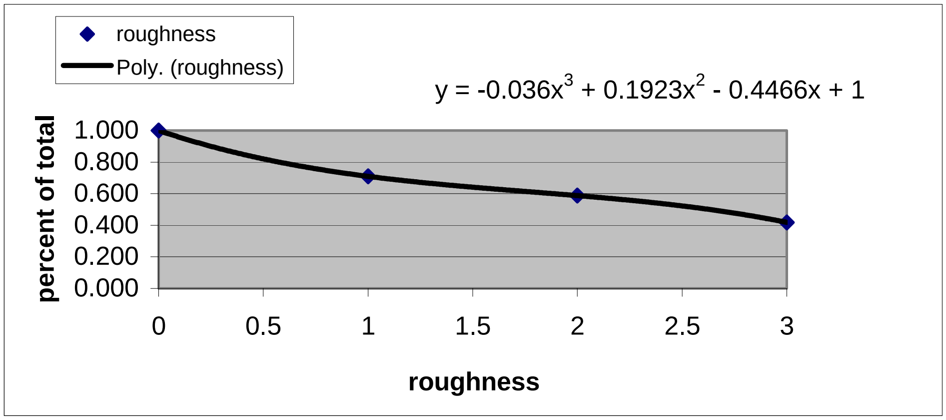
Roughness function based on decline in output at a location with average wind speed of 6.3 m/s



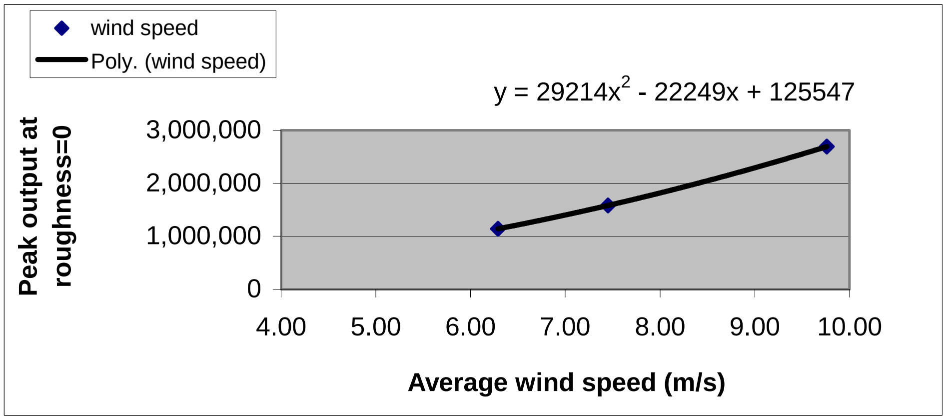
Roughness function based on decline in output at a location with average wind speed of 7.5 m/s



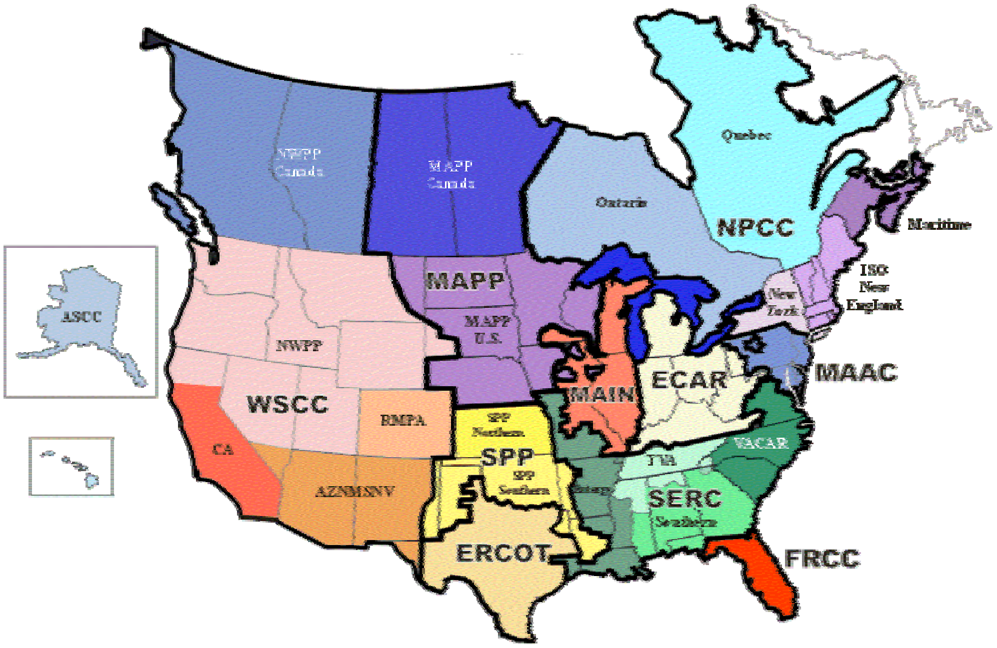
Roughness function based on decline in output at a location with average wind speed of 9.8 m/s



Average wind speed function derived from peak output at three locations.



Appendix I:
NERC Regional Map



ECAR - East Central Area Reliability Coordination Agreement
ERCOT - Electric Reliability Council of Texas
FRCC - Florida Reliability Coordinating Council
MAAC - Mid-Atlantic Area Council
MAIN - Mid-America Interconnected Network
MAPP - Mid-Continent Area Power Pool
    MAPP U.S.
    MAPP Canada
NPCC - Northwest Power Coordinating Council
    Quebec
    Ontario
    Maritime
    ISO New England
    New York

SERC - Southeastern Electric Reliability Council
    TVA
    Southern
    VACAR
    Entergy
SPP - Southwest Power Pool
    SPP Northern
    SPP Southern
WSCC - Western Systems Coordinating Council
    CA
    NWPP
    RMPA
    AZNMSNV

Appendix J:
Intracredit Coding Definitions

Credit Scenarios		
Code	**pts**	**Description**
EA1/18%elec	1	Reduction of 18% of site electric demand
EA1/46%gas	1	Reduction of 46% of site gas demand
EA1/38%elec	4	Reduction of 38% of site electric demand
EA1/100%gas	4	Reduction of 100% of site gas demand
EA2//LPV/5%	1	Low PV site(Detroit, 20yr lifespan), 5%REP target, no replacement after initial installation
EA2/HWind/5%	1	High Wind Site (8m/s, Roughness=1, 25 yr lifespan), 5%REP target, no replacement after initial installation
EA2//LPV/20%	3	Low PV site(Detroit), 20%REP target, no replacement after initial installation
EA2/HWind/20%	3	High Wind Site (8m/s, Roughness=1, 25 yr lifespan), 20%REP target, no replacement after initial installation
EA6/50%Grid50%Meth	1	50% grid (.23 FER) and 50% methane (1.9 FER) electric supply, 2yr contract
EA6/100%Wind	1	100% wind (37FER) electric supply, 2 yr cpntract
MR2/50%CDW	1	Achieve a CRR of 50%
MR2/75%CDW	2	Achieve a CRR of 75%
MR4/53%RCV	2	Recycled materials option 1
MR4/56%RCV	2	Recycled materials option 2
MR5/HMLC/LM8Km	1	High Mass Low Cost materials (21%MR) manufacturing distance=8Km
MR5/HMLC/LM800Km	1	High Mass Low Cost materials (21%MR) manufacturing distance=800Km
MR5/HMLC/LM&RM8Km	2	High Mass Low Cost materials (21%MR, 54%ER) Extraction and manufacturing distance=8Km
MR5/HMLC/LM&RM800Km	2	High Mass Low Cost materials (21%MR, 54%ER) Extraction and manufacturing distance=800Km

Exceeding LEED scenarios		
Code	**pts**	**Description**
EA2/HWind/20%/Replace	2	High Wind Site (8m/s, Roughness=1, 25 yr lifespan), 20%REP target, continual replacement
EA6/50%Grid50%Meth/75yr	1	50% grid (.23 FER) and 50% methane (1.9 FER) electric supply, 75yr contract
EA6/100%Wind/75yr	1	100% wind (37FER) electric supply, 75 yr cpntract
MR4/75%RCV	2	Recycled materials option 3